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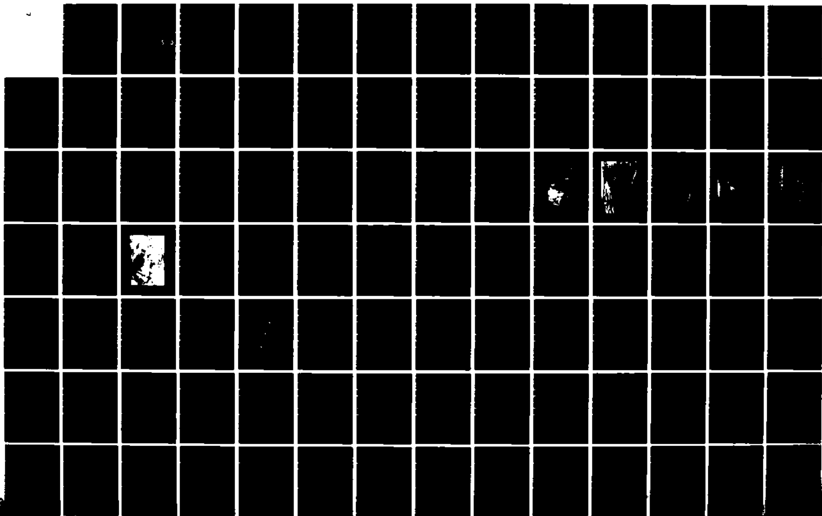

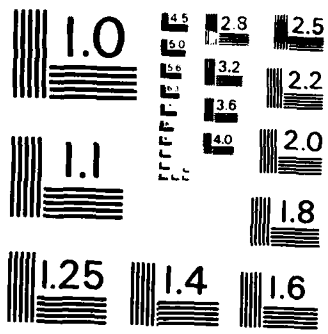

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TITLE: TECHNOLOGY DEVELOPMENT PLAN FOR DESIGN GUIDELINES FOR WAVE-INDUCED HYDRODYNAMIC LOADING ON STRUCTURES

AUTHOR: J. M. Dummer, LCDR A. E. Bertsche, and R. T. Hudspeth

DATE: March 1984

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TECHNICAL NOTE

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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METRIC CONVERSION FACTORS

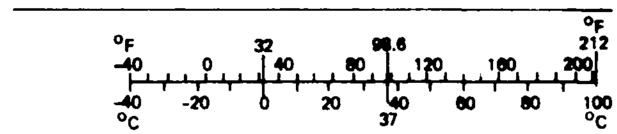
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	*kilograms*	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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This technology development plan reviews the role of the Naval Facilities Engineering Command (NAVFAC) in developing technology for the design of ocean structures subject to wave-induced hydrodynamic loading. Navy design requirements for ocean facilities and the technological deficiencies requiring further development to make these designs both reliable and economical are discussed. Specifically, the topic of wave force prediction technology is reviewed, and a summary of previous and current NAVFAC and Naval Civil

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Engineering Laboratory wave forces research is provided. A plan is outlined describing the development process necessary to achieve a comprehensive set of design guidelines for both rigid and compliant structures. Major subjects identified for inclusion in the proposed design guidelines include Morison equation force coefficient selection, Morison equation deterministic static analysis, Morison equation random dynamic analysis, diffraction theory analysis, combined large and small body loading analysis, and risk nalysis for Navy ocean structures. A discussion of each of the topics pertinent to these major items is provided.

Library Card

Naval Civil Engineering Laboratory
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EXECUTIVE SUMMARY

The wave forces exploratory development program was initiated in 1979 to develop and enhance NAVFAC design technology for the prediction of wave-induced hydrodynamic loads on Navy offshore structures. Previous Navy design efforts identified a number of deficiencies in this area, and more were anticipated for probable future designs. Several of these deficiencies are related to bottom-fixed lattice structures, moored breakwaters, single-point moorings, semi-submersible platforms, marine pipelines, and elevated causeways. In each example, the inability to accurately predict hydrodynamic loads on the proposed structure poses the threat of structural failure or could result in overly conservative, uneconomical structures. To mitigate these problems, the Wave Forces research project was developed. The proposed and completed research and development efforts are described in four Work Breakdown Structure (WBS) categories: WBS 1.0 Requirements Definition, WBS 2.0 Design Procedure Development, WBS 3.0 Design Guideline Development, and WBS 4.0 Project Management.

During the WBS 1.0 Requirements Definition phase the various topics pertinent to a comprehensive wave forces research and development program were identified. This was accomplished via a three pronged attack: first, a workshop of experts in the wave forces field was convened at the Naval Civil Engineering Laboratory (NCEL) in early 1979 to categorize the problem; second an assessment of the applicability of the Morison equation for estimating wave force loads on small member structures was conducted by an experienced offshore engineering firm; third a review of the technical literature regarding wave force predictive technology has been conducted by NCEL personnel. Because of the complexity and extent of the total problem, only those topics that had a high probability of technological payoff with a direct application to current or proposed Navy offshore structures were identified and selected for research and development under the WBS 2.0 Design Procedure Development category. This category was subdivided into research and development of wave force and kinematic prediction techniques. The wave force prediction category (WBS 2.1.0) was further subdivided into three research efforts, i.e., an evaluation and extension of the Morison equation (WBS 2.1.1), development of a force coefficient set for simultaneous waves and current (WBS 2.1.2), and the development of a high quality experimental wave force data base (WBS 2.1.3). The WBS 2.1.1 effort reviewed six different techniques to enhance wave force predictive technology relative to the standard Morison equation. A Fourier residue decomposition technique was selected as the most promising and resulted in the development of a four-term Morison equation. This new form of the Morison equation will be evaluated using the experimental data base developed in WBS 2.1.3. In addition, the wave force data base will be used to determine drag and inertia coefficients in the mixed drag and inertia dominance flow regime. The WBS 2.1.2 development of a force coefficient set for simultaneous waves and currents was initiated as a feasibility experiment in unidimensional oscillatory flow. This experiment demonstrated the variation in

the force coefficients due to the presence of the current. Additional wave/current coefficients will be determined using existing ocean data sets.

The kinematic prediction category (WBS 2.2.0) was further subdivided into two research efforts: a feasibility experiment to develop procedures for the simultaneous generation of waves and currents in a laboratory (WBS 2.2.1), and a follow-up large scale experiment to generate a comprehensive data base for the validation of existing wave and current kinematic prediction theories (WBS 2.2.2). The results from WBS 2.2.1 indicated that (for small scale experiments) there is some nonlinear interaction between the waves and a co-linear current. The difficulties inherent in the simultaneous generation of waves and currents in a laboratory were also identified and it was concluded that no laboratory facilities existed which could satisfy the large scale requirements of WBS 2.2.2. Consequently WBS 2.2.2 was deleted.

Only a small portion of the Morison equation force modeling topics has been actively investigated in the NCEL Wave Forces program; no diffraction theory wave force prediction topics have been selected for active research. The plan proposes preparation of a comprehensive set of design guidelines which would summarize the state-of-the-art (SOA) and standard-operating-procedures (SOP) wave force technology from the academic and industry communities as well as from the NCEL research topics. Design guidelines on the following subjects are recommended:

- Selection of Morison Equation Force Coefficients
- Morison Equation Deterministic Static Analysis
- Morison Equation Random Dynamic Analysis
- Diffraction Theory for Large Structural Members
- Combined Morison Equation and Diffraction Analysis for Composite Structures
- Risk Analysis of Navy Ocean Structures

The development of this proposed set of NAVFAC wave forces design guidelines is described in this document.

The WBS 4.0 Project Management category provides the integration of the other three WBS activities from the project inception to the design guidelines objective.

INTRODUCTION

This technology development plan describes the Naval Civil Engineering Laboratory/Naval Facilities Engineering Command (NCEL/NAVFAC) research program titled "Wave Forces on Ocean Structures." It is divided into three sections on increasing technological complexity. The first section, the Executive Summary, provides a broad overview of the program. The main part of the text describes the completed and proposed research program in a more comprehensive manner. However, to accommodate a broad spectrum of interested readers, the bulk of the technological details has been compiled into a series of appendixes referenced within the main text. The reader is encouraged to take full advantage of these appendixes, although the main body of the document is sufficient to provide a concise, yet comprehensive, description of the Wave Forces research program.

This technology development plan has been prepared to meet the goals of item V.B.1 in Reference 1 to "develop the capability to reliably estimate the magnitude and effects of wave and current forces on offshore structures." The plan reviews the role of the Naval Facilities Engineering Command (NAVFAC) in developing technology for design of ocean facilities; discusses Navy requirements for design of ocean facilities; identifies technological deficiencies requiring further development to make these designs both reliable and economical; and proposes techniques for reducing or eliminating deficiencies for facilities that will be part of the Navy's foreseeable requirements.

The objective of this plan is to outline the development process and describe the topics that must be included to achieve a comprehensive set of NAVFAC design guidelines for both rigid structures and compliant ocean platforms that respond dynamically to environmental loadings. The proposed design guidelines will include both (1) design specifications and (2) graphical/tabular design aids for wave and current hydrodynamic load analysis. The proposed design guidelines will also include the acceptable confidence limits for the design aids under real sea conditions. The technologies for development have been selected as those with high payoff values for the NAVFAC Design Program where "high payoff technology" is defined as those topics which maximize the capability to predict wave forces for foreseeable Navy structures while minimizing the research and development risks. In the selection process, the Navy's recommended design procedures were examined and a comparison made with state-of-the-art (SOA) and known industrial standard-operating-procedure (SOP) design techniques.

A review of the new DM 26.2 (Ref 2) has illuminated several areas in which the NAVFAC SOP for the "static equivalent" design of fixed offshore platforms should be updated to reflect recent technology development. Items that must be included in this update that are presently addressed in DM26.2 include:

(1) Selection of drag, inertia, and lift coefficients as functions of: dimensionless flow parameters (e.g., Reynolds number, Keulegan-Carpenter number, orbital velocity ratio, relative current

strength, etc.); roughness; member orientation; and the type and scope of the experiment regression analysis, the regression kinematics used to solve for the coefficient values.

(2) Discrete (force per unit length) Morison equation static analysis techniques which address: force model versus kinematics models; combined wave and current loading; member orientation; wave slamming; lift forces; mutual interference; and free surface effects.

In addition, the recently revised design guidelines in Reference 2 only address the designs for "static-equivalent" forces on "fixed" ocean structures. However, the "dynamics" of the interaction of the structure with the environmental loads cannot be treated by static-equivalent methods. The proposed technology development will expand the scope of the recently revised NAVFAC DM 26.2 to include the dynamic response of ocean structures. In addition, it will contribute to the present static-equivalent procedures as a consequence of the method of analyzing the dynamic motion of ocean structures. This will be accomplished by a linear decomposition of the environmental loads into the loads on a "fixed" structure plus the loads on an "oscillating" structure in a otherwise still water, thus substantially strengthening and improving the NAVFAC Design Program.

Failure to incorporate the above described static wave force analysis updates into NAVFAC SOP will result in the continuation of outdated and potentially inaccurate engineering analyses. Since dynamic analysis is not presently addressed, failure to incorporate the proposed dynamic analysis updates implies that the Navy has no foreseeable dynamic wave force analysis requirements, i.e., no foreseeable requirements for moored buoyant and/or deep water compliant structures. This is not the case as demonstrated in the following section of this report.

NAVFAC MISSION AND DESIGN REQUIREMENTS FOR OCEAN STRUCTURES

Naval ocean facility requirements in recent years have been characterized by a movement into deeper water. Examples are the TRIDENT submarine pier located in 130 feet of water in the state of Washington and the Tactical Aircrew Combat Training Systems (TACTS) towers in the ocean off North Carolina. Proposals for new facilities, including aircraft training ranges (e.g., the MOBILE RANGE concept, ECTACTS* and SOCAL** Range off the west coast), indicate this trend will continue.

In addition, further loss of foreign bases is possible, as well as an increase in political restrictions on present operating and training areas. Ocean structures offer a viable means of mitigating these losses and restrictions. These structures, however, may be sited in deep-water areas and will respond dynamically to their environmental loadings.

Reliable design procedures are required to design safe and economical ocean structures whether rigid or compliant. The dynamic response of the more compliant, deep-water ocean structures to environmental loadings

*ECTACTS - East Coast TACTS.
**SOCAL - Southern California.

forms the primary basis for this technology development plan and distinguishes these technologies from the present static equivalent capabilities in existing NAVFAC DM's. However, advancements in the SOP for the static equivalent design of rigid structures are also examined and addressed.

Navy Program Requirements

The Navy's requirements generate a demand for a broad spectrum of ocean facilities. Ocean engineering programs which illustrate this demand are briefly reviewed below. These applications illustrate that Naval ocean engineering requirements cover the entire spectrum of environmental loads analyses.

Bottom-Fixed Lattice Structures. A bottom-fixed lattice structure is the most frequently encountered industrial platform. Figure 1 illustrates one of four towers erected in 1977 as a Navy Military Construction (NAVMILCON) project under NAVFAC. These TACTS towers were erected in approximately 100 feet of water about 26 miles off Kitty Hawk, N.C.

There is a practical water depth limit (a complex function of the structural stiffness, geometry, and the applied loading) beyond which a lattice structure will respond with measurable excursions (i.e., becomes compliant). This dynamic response cannot be ignored in the design process since it is relevant to fatigue analysis and the prediction of maximum design stresses. Consequently, compliant ocean structures cannot be designed strictly by the static-equivalent methods used for relatively shallow water, rigid structure conditions. Such technology is not presently available in existing Navy design guidelines.

Moored Breakwater. A floating breakwater, anchored to the bottom, may be used as a wave attenuation device to protect nearshore facilities such as elevated causeways. The sloping float breakwater shown in Figure 2 is a row of flat, hollow panels which lie in an inclined plane. The lower ends of the panels are ballasted and rest on or near the seafloor.

The dynamic interaction of the mooring system with the structure contributes significantly to the natural frequency of the system; neither numerical nor analytical technologies are presently capable of accurately or reliably analyzing these dynamics. The added mass and radiation damping coefficients for complex structures having nonseparable geometry are not presently available from either numerical or experimental data.

Single-Point Moorings. The Offshore Bulk Fuel System (OBFS) will provide an offshore fuel facility capable of supporting a landing force during an amphibious operation. A Single-Point Mooring (SPM) (Figure 3) is one of the major components of the system. The SPM will be capable of mooring tankers of up to 70,000 DWT in deep water in sea state 5 conditions. Analysis techniques are not presently available for designing moored systems which are subjected to large amplitude, low frequency wave drift forces. The dynamic interaction of a moored structure with these wave drift forces is a highly nonlinear phenomenon which industry has treated largely through the use of tentative empirical approximations.

Flexible Floating Structures. Another component of the OBES system is the Dracone (Figures 3 and 4). These flexible bladders float on the free surface and store fuel during the early phases of an amphibious operation. Analysis technology is not presently advanced enough for designing large, flexible structures which respond dynamically to environmental loadings.

Elevated Causeway. Amphibious assault operations and over-the-shore logistics operations are designed to be conducted over undeveloped beaches where port facilities are not available. The Navy is developing a "Container Offloading and Transfer System" (COTS) for offloading nonself-sustaining (NSS) container ships in support of these operations. An elevated causeway (Figure 5) is a key element of this system.

The causeway will eliminate the surf conditions in the lighterage-to-shoreside interface operations. By elevating the causeway sections on piles above the surf zone and extending the causeway sections seaward, deep draft logistic barges may be accommodated. Analysis technologies are not presently available for analyzing the complex dynamic interactions of jack-up barge systems as the barge is being elevated. The critical installation phase, when the barge just clears the air-sea interface, involves a time domain transition from wave and current loading to wave, current, and wind loading coupled with time variant buoyancy/structural loading and random wave slamming loads. Commercial firms treat this problem totally through the use of tentative empirical approximations.

Open-Sea Pier Facilities. A trend in the development of ports toward the use of open-sea facilities has become evident. This was brought about primarily by the increase in vessel draft, but also of importance have been the reduction of available waterfronts and the desire to conduct potentially hazardous loading and offloading operations in remote locations. The latter factor is of considerable importance to the Navy.

Ordnance activities in today's Navy are being conducted in developed port areas. Explosive-Safety-Quantity-Distance (ESQD) arcs drawn for many of these Naval facilities indicate that safety standard violations exist and that waivers must be negotiated with local authorities. This affects fleet readiness, and alternative facilities are needed.

One alternative, considered in a naval ammunition logistics system (NALS) study, is the use of open-sea pier facilities. A conceptual drawing of one such facility is shown in Figure 6. These piers may be erected in deep water beyond the ESQD limits.

Technologies are not presently advanced enough for designing ocean structures that can be placed in relatively deep water where they will be subjected to moored vessel impact loadings as well as wave and current hydrodynamic forces.

Transway. As a result of projecting future needs of amphibious assault units, it has been determined that the elevated causeway system (ELCAS) will be inadequate for providing the high volume of containers required onshore from NSS container ships (container ships without

heavy-load-handling capability). The use of ELCAS to support amphibious assault operations will require a temporarily moored, floating, load-handling facility (e.g., crane-mounted barge/ship) used in conjunction with numerous Navy lighters and causeway ferries. This lightering operation is manpower intensive and requires large shipping volume requirements. The Navy is developing concepts for more direct container offloading systems.

One concept is to offload the NSS container ships directly to a shore-fast facility (Transway), which would extend from shore out to water depths sufficient for maneuvering a container ship. Overall lengths of 2,500 feet from shore out to water depths of 50 feet are projected requirements. A range of Transway concepts (e.g., pile-founded piers, moored piers, semi-submersible piers) are under preliminary development and parametric evaluation. Procurement of the Transway system is projected for early to mid-1990s.

Semi-Submersible Platforms. The semi-submersible configuration, because of its large dock area and stability, is frequently selected as a platform from which to conduct fixed-base operations in the ocean. These platforms, either singly or in combinations, have been considered for a number of applications. They may be suited to employment as logistic platforms, instrumentation platforms, ocean laboratory stations, or other similar use. A typical configuration is shown in Figure 7.

Analytical techniques are required for designing ocean structures which respond dynamically to forces which are the result of the hydrodynamic interaction between large (diffraction regime) members and small (Morison regime) members.

Marine Pipelines and Cable Runs. Marine pipelines and cable runs are used in many Naval facilities for fuel and oil transfer, electrical power, and communications. Waves frequently damage these structures (Figure 8). Design procedures are presently not advanced enough for analysis of the dynamic response of these structures.

The OBFS currently under development (see Figure 3) provides two applications which illustrate this need. A 10,000-foot-long, 8-inch-diam fiberglass-reinforced plastic (FRP) pipeline will be used to transfer fuel from the Dracone pumping station to the beach. Electrical power will be delivered to the pumping station through an unanchored electrical cable. Both the pipeline and cable will pass through the surfzone and will be subjected to wave loading over a majority of their length. The "static-equivalent" design methods in Reference 3 are not capable of providing design standards for the dynamic response shown in Figure 8.

Offshore Personnel and Equipment Transfer Platform, Andros Island, the Bahamas. Offshore platforms may be suitable for use at the AUTEC* range to facilitate transfer of equipment and personnel between a shore base and the surface ships and submarines undergoing trials. Due to the unsheltered sea conditions at the projected transfer site, which is on the edge of the reef forming the western rim of the "Tongue of the Ocean," conventional berthing facilities are considered inadequate. A

*Atlantic Undersea Test Evaluation Center.

study (Ref 4) was undertaken in which 13 different offshore structural concepts were evaluated. Of these, the following were recommended for further evaluation:

1. Hydraulic jack-up platform

2. Gravity platform

3. Tension leg platform

4. Floating hull with propulsion

5. DeLong self-evaluating platform

6. Concrete platform with breakwater

Ocean Ranges. The success of the TACTS and recent advances in electronics equipment for simulation and tracking have led the way in development of ocean ranges. Today, three ocean ranges are in operation. The U.S. Navy's ECTACTS offshore Kitty Hawk, N.C., employs bottom-fixed lattice platforms. The Air Combat Maneuvering Instrumentation (ACMI) range at Tyndall AFB, Fla., employs small bottom-resting gravity platforms in the Gulf of Mexico; a second ACMI range, located offshore Sardinia, employs discus buoys. The erection of other East Coast TACTS off Charleston and in the Gulf of Mexico is being considered, and the expansion of the TACTS at Kitty Hawk (Ref 5) is also a possibility. TACTS facilities for the West Coast are also being planned. The need for these ranges is strong, and as many as eight could eventually be positioned around the continental United States (Ref 5).

Program Requirements Summary

The previous examples, though not exhaustive, demonstrate that Navy requirements span the broad spectrum of ocean facilities from moored bladder structures to submarine cables and from rigid lattice structures to the buoyant, compliant semi-submersible platform. In general, these requirements are unique to the Navy in configuration or application; consequently, they pose specific and unique design problems. Loading, response, and reliability analyses as well as cost minimization studies are complicated by the lack of applicable design procedures. For those examples in which the Navy requirements approximate those of private industry, Navy design technology lags behind that of private industry. This lag poses problems in initiating and monitoring contracts for engineering design services.

In addition, current industrial SOP for design often rely on tentative empirical approximation methods. These methods require experimentally derived coefficients (which may not be suitable for the specific Navy application) and expensive model studies to calibrate or verify the empirical method employed. The uncertainties inherent in such a design procedure necessarily increase the risk of failure and decrease the overall structural reliability. To mitigate these uncertainties, designers are obliged to increase the safety factors, thereby increasing the cost of the structure. This design procedure can be honed to some degree for

private industry structures where the application and configuration remain unchanged for many structures. That is, expensive model tests are required for the first generation of structures to calibrate and validate the design. Successive generation designs are then updated based on the experience and knowledge gained from the previous generation. In this way the high cost of the first generation can be amortized over a number of generations. Navy structures generally do not benefit from the bulk of this experience since they do not conform to industry structures in application and configuration. Consequently, if the empirical approximation methods are to be used, they will often require expensive model studies to validate the design.

Also, some lag exists between private industry's SOP for design and SOA technology. That is, SOP is not updated immediately to reflect SOA knowledge because industry SOP is viable and economical, thus maintaining risk and profit at acceptable (but not optimal) levels.

Recognizing the uniqueness of the Navy requirements described above and the lag between existing Navy design technology and the SOA and SOP technology levels of academia and private industry, NCEL has subdivided the wave forces research program into three major efforts (work breakdown categories):

(1) Requirements Definition. This effort employed Navy, university, and private industry experts to review Navy requirements and identify those research subjects which would be of significant benefit for anticipated Navy structures and have a high probability of payoff. The subjects identified are static and dynamic Morison equation analysis (and associated coefficient selection), and linear and nonlinear diffraction theory analysis. Each of these subject areas has been broken down into specific research topics.

(2) Design Procedure Development. The specific research topics identified above in (1) were reviewed relative to their significance to anticipated Navy design requirements. Those specific topics which, again, had a high probability of payoff were selected for active research under the NCEL wave forces program. Under this effort, research has been conducted regarding the design procedure topics of wave/current kinematics, revision of the Morison equation, and generation of wave force and coefficient data bases.

(3) Design Guidelines. This effort synthesizes the work completed in (1) and (2) above, as well as a literature review of SOP and SOA technologies, into a comprehensive set of design guidelines.

The above descriptions of the three major programmatic efforts relative to the Navy's design requirements are summarial. They are described in more detail in the next section.

WAVE FORCES RESEARCH PROJECT: PAST, PRESENT, AND FUTURE

Introduction and Application

The work breakdown structure (WBS) for the Wave Forces project has been adopted from the guidance provided in MIL-STD-881A. It provides a comprehensive definition of the work necessary to fulfill project objectives in terms of a hierarchy of work categories. There are three major categories of technological development in the WBS (see Figure 9):

- Requirements Definition (WBS 1.0)
- Design Procedure Development (WBS 2.0)
- Design Guidelines (WBS 3.0)

In addition, a fourth category, Project Management (WBS 4.0), is provided for planning, monitoring, and integration of the project efforts. Descriptions of the WBS work elements are provided below.

WBS 1.0 Requirements Definition

This category provides for the definition of the technical requirements of the project. It summarizes the technical topics requiring investigation for improved wave-current loading prediction techniques, it identifies and reviews other on-going wave force developments, and it identifies high payoff technology topics for Navy development. This category includes five tasks all of which have been completed (see Figure 9):

- Wave Force Research Workshop (WBS 1.1)
- Morison Equation Assessment (WBS 1.2)
- Wave Current Kinematic Literature Review (WBS 1.3)
- Long-Term Sensor Platform Preliminary Investigation (WBS 1.4)
- Wave Forces R&D Review (WBS 1.5)

WBS 1.1 Wave Force Research Workshop. A 2-day seminar on the environmental loads on fixed offshore structures was convened at NCEL on 19 and 20 April 1979. The workshop agenda, a list of participants, and a list of the 16 recommendations prepared as a result of the workshop are given in Appendix A. These recommendations for technology developments form the basis for this technology development plan and the initial wave forces research development plan (Ref 6). Many of these recommendations have either been completed or modified substantially by subsequent developments. The recommendations by NAVFAC engineers and university experts reflect technology deficiencies in the NAVFAC design program for ocean facilities. As a consequence of the broad spectrum of ocean

engineering experience at this research workshop, these recommendations were especially suited for developing the well-integrated technology development plan of Reference 6.

WBS 1.2 Morison Equation Assessment. As a result of the recommendations listed in WBS 1.1 the applicability of the Morison equation for estimating the wave force loads on small-member, ocean structures was to be assessed. This assessment was conducted by Woodward-Clyde Consultants, an experienced offshore consulting engineering firm, so that a review of private industry's SOP for small-member loading analysis could be achieved. Reference 7 provided a critical assessment of the Morison equation.

Three tasks that would enhance the NAVFAC capability to predict wave forces and provide a basis for updating the Navy's Wave Force Design Guideline were identified:

1. Improvement and extension of the Morison Equation

2. Improvement of the description of sea-state and water particle kinematics

3. Conducting basic research on fluid-structure interaction dynamics

Tasks 1 and 2 were incorporated into the initial wave forces project research development plan (Ref 6). Task 3 was pursued under NCEL's internal independent research program and, consequently, is not duplicated in this program. A more detailed explanation of these tasks is provided in Appendix B.

WBS 1.3 Literature Review of Kinematic Predictive Techniques for Combined Wave-Current Flows. One of the high-payoff technology areas identified (Ref 7) was the improved description of the water particle kinematics. Of particular concern to ocean engineers is the modeling of combined wave and current flows. For lack of a better method, existing SOP simply linearly superimposes the modeled current velocity profile with the theoretical horizontal velocity component resulting from the oscillatory wave motions. This method is thought to be inaccurate for nonlinear combinations of waves and currents; however, by convention, this modeling technique is used extensively due to its simplicity. Because of the strong dependence of the predicted wave-current force values (using the Morison equation) on the local magnitude of the combined (wave-current) velocity, improvements in methods to predict velocity magnitudes would substantially improve the accuracy of existing wave forces prediction techniques.

A literature review of this topic was conducted for NCEL by Prof. Fredric Raichlen (Ref 8). The purpose of this effort was to review various aspects of wave current interactions as they relate to the details of the hydrodynamics problem. The review was mainly directed toward the literature which dealt with experimental investigations and related problems. This review disclosed that there exists a lack of experimental data of sufficient accuracy and reproducibility. This high quality experimental data base is required to provide a comparative data

base for existing and proposed theories on wave-current interaction. This review concluded that an experimental program was required to develop an accurate and reliable data base for wave-current interactions.

The review also examined the various theories for the prediction of linear and nonlinear interaction between waves and currents. The most basic of these theories (and the most commonly used) is a linear superposition of the respective orbital and current velocity components. This theory is thought to be too inaccurate for the kinematics analysis of finite amplitude waves interacting with currents of significant magnitude such that the wave field characteristics of wave length and steepness are modified by the presence of the current. This review proposed that a numerical solution of this problem developed by G.P. Thomas (Ref 9) be critically examined and compared to experimental measurements. This theory appears to be the most likely candidate to provide an accurate kinematics analysis technique for a wide range of engineering design conditions in which waves and currents were present simultaneously.

A more complete overview of this literature review is provided in Appendix C.

WBS 1.4 Long-Term Sensor Platform Preliminary Investigation. Although the preliminary investigation of the long-term sensor platform described in Reference 5 was not funded by the Wave Forces project, it was conducted simultaneously with the initial Wave Forces Project Requirements Definition (WBS 1.0) phase. For this reason, the hydrodynamic loading analysis requirements established in this preliminary investigation were particularly pertinent to the Wave Forces project Development Plan described in Reference 6.

Reference 5 recommended technology developments in five specific areas: (1) site analyses, (2) load analyses, (3) structural analyses, (4) foundation and mooring analyses, and (5) installation operations and procedures (see Appendix D for a more complete descriptive breakdown on these areas). The significance of each of these items was identified in relation to the design process as shown in Figure 10. This fundamental review of the requisite components of a comprehensive design process methodology as well as the recommendations regarding hydrodynamic load analysis were incorporated with the results WBS 1.1 and 1.2 into the 27 recommended Wave Forces technology development topics described in Reference 6 (also shown in Appendix D).

The review of the structural analyses techniques during the preliminary investigation of the long-term sensor platform preliminary investigation also highlighted the importance of accurate hydrodynamic load prediction techniques to provide accurate forcing functions for dynamic structural response analyses. This dynamic emphasis is reiterated in the design guideline recommendations of this report since it is necessary for the analysis of compliant structures.

WBS 1.5 Wave Forces R&D Reviews. The Wave Forces project is not unique in its endeavors to extend wave forces prediction technology. Numerous other government agencies (both U.S. and foreign) and private industry investigations have been conducted with regard to the various aspects of the wave forces topic. In accordance with the "WBS 1.0 Requirements Definition" theme and in support of "WBS 4.0 Project

Management" needs, an effort has been directed toward continuous monitoring and review of external wave forces research and development activities. This effort has not been exhaustive since the wave forces topics are too numerous and the literature too voluminous to allow a complete review. However, this review has been comprehensive to the extent that the current SOP and SOA design technology is monitored. To date, in excess of one hundred publications have been received and examined in an effort to stay abreast of technology and avoid duplication of research efforts.

Input on the SOP and SOA technology has also been obtained from courses such as "Dynamics of Sea Based Structures," which reviewed the subjects of wave forces on ocean structures, random vibrations, and wave theories relative to dynamic structural analysis, and "Design of Fixed Offshore Platforms - A Comprehensive Review" (Ref 10). The latter course described the petroleum industry static analysis SOP for the topics of wave force computation, design storm selection, spectral analysis application, and risk evaluation. Overall, this course presented fundamental summary of the petroleum industry design SOP for fixed platforms from initial engineering conception through construction, installation, and operation. A detailed description of this course is available in Reference 10.

In addition, personal communication with industry and university experts in the wave forces field has been maintained. Information regarding the NCEL Wave Forces research is disseminated and constructive comments regarding the research applicability, program goals and objectives, and future research recommendations are received. This feedback has been beneficial in establishing and re-evaluating the WBS 1.0 Requirements Definition and in organizing and coordinating the WBS 4.0 Project Management efforts.

Summary of WBS 1.0 Requirements Definition Activities. Activities ranging from a formal research seminar to informal communications with experts in the wave forces field have been, and are being, conducted to define, re-evaluate, and update the requirements for wave force prediction technology. These activities are conducted in direct support of WBS 4.0 Project Management efforts to establish a step-wise continuous, comprehensive research program relevant to proposed and anticipated Navy structures. These activities culminated in high-payoff technology development recommendations of Reference 6 and are continued in the design guideline recommendations of this report.

WBS 2.0 Design Procedures Development

This category provides for the development of that technology offering the greatest potential for high payoff in advancing the Navy's capability to predict wave forces. The Wave Force Research Workshop (see Appendix A) and References 5, 6, and 7 specifically identified two recurring task areas necessary for a comprehensive design analysis which required additional research and development. These technology areas are (see Figure 9):

- Improve and extend the Morison Equation.
- Improve the description of water-particle kinematics.

<u>WBS 2.1 Wave Force Prediction Techniques</u>. The Morison equation has been shown to be a reasonably accurate predictor for computing the maximum static wave force on a slender body member. This has been demonstrated for both inertially dominated and drag dominated flow regimes. This has not, however, been the case for the dynamic prediction of the cyclic force history, particularly in the mixed inertial/drag dominance flow regime. Sarpkaya (Ref 11) has shown that in some instances the dynamic force predicted by the Morison equation may deviate from measured values in a U-tube experiment by more than 30%.

This subcategory provides for the development of technology that will enhance the prediction capabilities of the Morison equation. These developments are focused at extending the applicability to the regime of mixed inertial-drag dominance. In addition, a set of force coefficients (C_m, C_d) for the above extended equation, as well as combined wave-current flow regimes, are developed within this subcategory. Lastly, a high quality, carefully controlled experimental wave force data base will be produced for validation of existing and future wave force prediction techniques.

<u>2.1.1 Extension of the MOJS Equation</u>. The objective of this investigation was to extend the accuracy of the Morison, or MOJS*, equation for estimating wave force loads in the mixed drag-inertia dominance regime. This effort is summarized in Reference 11.

Reference 11 reviewed the historical origin of the Morison equation as well as some of the other subsequent techniques for computing wave forces on small member structures. In particular, six specific techniques were reviewed in detail to estimate the most promising technique for minimizing the residual errors in the comparisons between measured and predicted forces.

Of the six techniques reviewed in Reference 11, the Fourier residue analysis was the method selected for reducing the residual error. Originally proposed by Keulegan and Carpenter (Ref 13), this method expands the residuals in the error between the measured and predicted force in a Fourier series of odd-order harmonics and computes the Fourier coefficients which reduce the residual errors in a best least-squares sense. Appendix E contains both the generalization of a four-term MOJS equation and a specific four-term MOJS equation with additional empirically determined coefficients computed from harmonic flows past a circular cylinder in a U-tube experimental facility.

<u>WBS 2.1.2 Wave-Current Effects on Hydrodynamic Forces and Coefficients</u>. The objective of this task was to develop a set of experimental force coefficients applicable to harmonically oscillating flows combined with current flows. In addition, the effect of current-induced wake biasing on the modified Morison equation was examined. This effort is summarized in an NPS report (Ref 14).

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*The equation is often referred to as the Morison equation. However, because it was developed by <u>M</u>orrison, <u>O</u>'Brien, <u>J</u>ohnson, and <u>S</u>chaff, it has been abbreviated to MOJS equation, reflecting the first letter of each name (see Ref 12).

The four-term MOJS equation developed in Reference 11 was evaluated in Reference 14 using data obtained from harmonic fluid flow past a uniformly moving circular cylinder in a U-tube. Both smooth and artificially roughened circular cylinders of two different diameters were towed at a uniform speed in simple harmonic fluid flows. A generalization of the two-term MOJS equation was used to compute the drag and inertia coefficients over a range of Reynolds numbers, Keulegan-Carpenter numbers, Beta parameters (where Beta is defined as the ratio of the Reynolds number to the Keulegan-Carpenter number), and relative velocity ratios between the uniform tow speed (i.e., steady current) and maximum water particle velocity. These two coefficients were then used to compare the predicted fluid forces on the cylinder by both the standard two-term MOJS equation and the empirically modified four-term MOJS equation from Reference 11. The limited comparison indicated lower residual errors using the empirically modified four-term MOJS equation from Reference 11 with the two coefficients computed from the two-term MOJS equation.

The eight conclusions which resulted from this investigation are summarized in Appendix F.

The feasibility of obtaining wave-current superposition force coefficients in unidimensional oscillatory flow experiments has been demonstrated in Reference 14. The applicability of such a coefficient set for three-dimensional problems has yet to be determined. A wave-current force coefficient set is being obtained from further analysis of existing ocean data sets obtained under combined wave and current loading. This analysis will be conducted using the system identification technique which is useful for noisy nonlinear ocean data.

WBS 2.1.3 Experimental Wave Force Data Base. To validate a hydrodynamic wave force model such as the four-term MOJS equation described in the section on WBS 2.1.1 and in Appendix E, a high quality data base for hydrodynamic wave forces is required. Ideally, such a data base would be acquired from an open ocean experiment in which the pertinent parameters had been carefully and selectively controlled and measured over a wide range of experimental conditions. An exhaustive literature review indicated that no such experiment had been conducted to date and that careful and selective control of an open ocean experiment is contrary to the random character of the real ocean environment. Feasibility studies for the use of the TACTS towers for such an experiment showed that while it is possible to obtain open ocean wave force data, correlation of that data with the simultaneous kinematics and surface displacement measurements for a confused random three-dimensional sea may be a task beyond current state-of-the-art measurement and data reduction techniques. This information, coupled with the projected costs and lack of fundamental physical knowledge for three-dimensional unsteady turbulent flow field effects, indicated the risks of performing such an experiment outweigh the potential value at this time.

An alternative (though less desirable) method of acquiring such a data base would be through a comprehensive series of laboratory tests that would satisfy the dichotomy of establishing the precision, order, and control of a well-conceived laboratory investigation and yet would maintain close modeling similitude with real ocean waves. A series of experiments was devised (employing the Oregon State University Wave Research Facility) that will satisfy this dichotomy as closely as

state-of-the-art capabilities permit. This series will provide a data base comprised of the total instantaneous in-line and transverse forces and the total moment on a smooth vertical cylinder as well as the instantaneous local in-line and transverse forces, the instantaneous local pressure and kinematics fields, and the water surface displacement time history. The experiment was designed to ensure the quality of the data base, similitude with real ocean two-dimensional waves, and the pertinence of the data for future force model validation efforts. Presently, the data base is to be used for force coefficient determination, validation of the four-term MOJS equation, and comparison of the theoretical and measured pressure and kinematic fields. The experiment and data reduction are described in detail in Reference 15.

WBS 2.2 Kinematics Prediction Techniques. The inability to provide accurate values of wave and current kinematics is a major source of error in all applications of the Morison equation (Ref 6). This WBS category (see Figure 9) provides for the development of improved techniques to characterize water particle kinematics resulting from the combined influence of waves and currents. Specifically, experimental procedures for conducting controlled, repeatable laboratory measurements of water particle velocities under the combined influence of waves and current were developed. These experimental procedures were employed in a small-scale experiment to investigate the interaction of co-linear waves and currents. The purpose of this experiment was two-fold. First, the experiment was intended to initiate an interactive wave/current kinematics data base (albeit small-scale) for comparison with, and validation of, linear and SOA kinematics prediction theories. Second, the experiment was a feasibility test to examine critically the applicability of the developed experimental procedure for the acquisition of a large-scale wave/current kinematics data base.

WBS 2.2.1 Develop Experimental Procedure. The purpose of this task was to provide experimental kinematics data for wave/current interactions. Prior to the commencement of this task, a literature review (WBS 1.3 and Ref 8) was conducted to evaluate linear and nonlinear wave-current interaction kinematics prediction theories and to review past experimental efforts related to wave-current interaction measurement techniques. Advantages and disadvantages of these past efforts were noted. Based on these findings, a small-scale experimental procedure was developed (Ref 16). Devices were developed and fabricated that effectively introduced a uniform current into the wave flume. In addition, a two-dimensional laser-Doppler velocimeter (LDV) was incorporated to measure water particle velocities. The LDV has the distinct advantage of being a nonintrusive velocity measurement system.

A small amplitude (nearly linear) cnoidal wave form was selected for the initial set of experiments. Since the experiments were conducted in a wave flume, the direction of wave propagation and current flow was necessarily co-linear. Wave interaction with both favorable (flow in the direction of wave propagation) and adverse currents were examined. Water particle velocities due to current action only were measured first, and then due to wave action only. The experiment was then conducted with the current interacting with the waves, and the combined interactive velocity was recorded. Comparisons of the measured water particle

velocity for combined wave-current interactive flow were made against (1) the vectorial addition (linearly superimposed) of the measured velocities due to currents only plus velocities due to waves only, and (2) numerically predicted velocity values based on the theory by Thomas (Ref 9).

Two significant findings resulted from this effort. First, the feasibility of conducting a controlled experiment of this type has been demonstrated on a small scale. Second, for relatively small-amplitude waves (nearly linear), it appears that linear superposition of the velocities reasonably predicts the measured total velocity. Consequently, it was concluded that, at the small scale of these experiments and for the nearly linear waves employed, no nonlinear interaction between the waves and currents (either favorable or adverse) was apparent in the combined measured kinematics.

In a sequel experiment (Ref 17), the interaction of currents with highly nonlinear finite amplitude waves was examined. A solitary wave form propagating on an adverse current was selected to accomplish this objective. As before, kinematics measurements were obtained for the waves alone, for the current alone, and then for the combination of the two. The vectorial addition (linear superposition) of the component velocities (waves alone plus current alone) deviated from the measured combined value by about 10% at various elevations in the water column. Although the linear superposition technique would appear to be reasonably accurate, it should be noted that a 10% velocity error will result in an error of approximately 20% in a drag force computation. Raichlen and Lee (Ref 17) also found that a system of trailing harmonic waves (generated when the solitary wave encountered the current generation apparatus in the wave flume) was significantly affected by the presence of the current. That is, developing wave forms interacted with an adverse current in a nonlinear fashion during these small-scale experiments.

Because of the increased orbital velocities of finite-amplitude waves relative to small-amplitude waves, it was difficult - even for these small-scale experiments - to achieve a current of sufficient magnitude to affect the waves. The ratio of the average current velocity to the maximum horizontal wave-induced orbital velocity was approximately 0.4. Larger waves on relatively larger currents would probably produce more nonlinear interaction effects. It was recommended that this research be continued on a much larger scale which would be more pertinent to the real ocean environment. Furthermore the large-scale research should include obliquely and perpendicularly incident waves and currents as well as the co-linear cases investigated here. However, while large-scale facilities are available for producing either waves or currents independently, no known facility can simultaneously produce large-scale waves and currents to achieve a steady-state interaction within the confines of the facility.

A general description and the conclusions as well as some of the experimental results from References 16 and 17 are presented in Appendix G.

<u>WBS 2.2.2 Develop Experimental Wave Current Data Base</u>. As stated in the requirements definition of WBS 1.3, a large-scale, high quality interacting wave/current kinematics data base is required for the comparison and validation of linear and nonlinear SOA kinematics prediction theories. It has been shown that even a relatively small

error in the predicted kinematics can result in significant errors in the predicted drag forces. However, based on the above feasibility studies, the development of a wave-current data base must be deferred until large-scale experimental facilities are available. The development or procurement of these facilities is beyond the scope and resources available to the NCEL Wave Forces project.

WBS 3.0 Wave Force Design Guidelines

The overall goal of the Wave Forces project is to enhance existing Navy wave force guidelines by integrating technology developments of this project, as well as other state-of-the-art wave force developments, into existing Navy design aids. This WBS category provides for the accomplishment of this goal. Under this category, guidelines on the following topics are proposed (see also Figures 9 and 11).

- Selection of Morison Equation Coefficients
- Morison Equation Deterministic Static Analysis
- Morison Equation Random Dynamic Analysis
- Diffraction Theory for Large Structural Members
- Combined Morison Equation and Diffraction Analysis for Composite Analysis
- Risk Analysis for Navy Ocean Structures

WBS 3.1 Selection and Parametric Dependency of MOJS Equation Coefficients. The origin of the MOJS equation was reviewed in Reference 7, and generalizations of this equation were reviewed in Reference 11. The following dimensionless parameters were identified in these reports as those relevant for correlating wave forces on small members: Reynolds number; Keulegan-Carpenter number; Froude number; frequency parameter, Beta; relative roughness; water particle velocity ratio, omega; and the Dean data conditionality parameter. Figure 11 identifies the level 3 tasks required to provide guidelines for evaluating the dimensionless parameters required to correlate the drag and inertia force coefficients in the MOJS equation. In addition, guidelines must be provided which distinguish between field and laboratory data for vertical, horizontal, or inclined members, and between the various numerical regression analysis procedures employed to determine the coefficients from the measured data. The effects of using theoretical rather than measured kinematics in the regression analysis must be specified. The guidelines must include the effects of dynamic, relative motion interactions on both in-line and transverse forces and moments and must be applicable to both periodic and random wave forces. The effects of cylinder roughness on the force coefficients should be identified and a comparison made of the experimental error introduced when artificial roughness is employed to model marine growth. As previously described (Ref 14 and Appendix F), the effects of currents on the force coefficients is being investigated and must be included in the guidelines.

A detailed description of the work required to compile such a guideline set is provided in Appendix H for each of the level 3 coefficient selection topics identified in Figure 11. An example of a unified tabular format is identified in Appendix H. Such a format is required for the level 3 topics to ensure uniformity, clarity, and comprehensibility and to facilitate the inclusion of these guidelines into future Navy design manuals. In addition, a schedule is presented for each of these topics in Appendix H.

WBS 3.2 Morison Equation Deterministic Static Wave Force Analysis. Existing NAVFAC guidelines for the computation of wave loading on small-diameter members using the static analysis technique are inadequate. Updates are required to reflect technology advances in the SOA and SOP design techniques employed by the offshore petroleum industry. Seven pertinent level 3 research tasks are identified in Figure 11 to accomplish the objective for static wave force analysis. These tasks are also relevant to the random dynamic loading analysis but are not repeated in Figure 11 for the sake of brevity. As before, a series of design guidelines, documenting the SOA and SOP design techniques for each level 3 task, is anticipated. Each task-specific guideline will be prepared by an expert in that particular field. Since some overlap must necessarily occur between the Figure 11 level 3 tasks associated with "Force Coefficient Selection," "Deterministic Static Analysis," and "Random Dynamic Analysis," the same expert may provide input on the overlapping topics. For example, the expert documenting the effects of currents on the force coefficients might also be expected to describe the SOA and SOP for deterministic static or random dynamic wave force modeling when waves and currents are both present.

The design guidelines will be prepared to summarize both the SOA and SOP technology for the selection of wave kinematics and the force coefficients relative to specific force models. Guidelines which incorporate present NAVFAC/NCEL wave/current kinematics and coefficient research will also be provided. In addition, wave force analysis effects due to member orientation, wave slamming, transverse forces, mutual member interference, and free surface corrections will be identified in the guidelines.

The work to be compiled in the above set of guidelines is described in detail in Appendix I, including examples of possible unified tabular formats. Such a format will be helpful to ensure uniformity, clarity, and comprehensibility in the guidelines. A schedule for the preparation of this guideline set is also provided in Appendix I.

WBS 3.3 Morison Equation Random Dynamic Wave Force Analysis. NAVFAC guidelines for the computation of hydrodynamic loading on small-diameter members using a dynamic wave force analysis are nonexistent. As ocean structures are sited in deeper water or as the safety factors employed in specifying the structural members decreases, the structures become less rigid and, hence, more compliant to wave/current loadings. This compliancy necessitates another phase in the design process; i.e., the random dynamic analysis phase. The hydrodynamic loading in this phase must be described since this provides a significant component of the time-dependent forcing function for the structural analysis. To accomplish this task, nine level 3 research tasks, identified in Figure 11,

are relevant to the random dynamic wave force analysis topic for small members. Again, a set of design guidelines documenting the SOA and SOP design techniques for each of these nine tasks is requi ed. As before, each task-specific guideline will be prepared by an expert in that particular field. New research is not expected in the preparation of these guidelines but, rather, a summation of previous relevant research and experimental results. The tasks identified under the "Deterministic Static" topic of Figure 11 are also generally pertinent to the random dynamic analysis, but they will not be repeated unless some discrepancy exists between the corresponding static and dynamic tasks.

The design guidelines will summarize the relevance of probability and statistics to asymmetrical wave theory, extreme value occurrence, and spectral wave and force descriptions. Directional wave spectra applications will be identified. Guidelines will document the effects of combined waves and currents and wave slamming in random dynamic seas as well as the compliancy effects on coefficient selection. The nonlinear Stream Function wave theory tables will be revised to correct the breaking wave case (case D) (see Ref 18), and a guideline will be provided for their use and application. In addition, the frequency and time domain dynamic solution techniques will be reviewed and compared. The accuracy and computational requirements of both solution techniques as well as a review of the frequency domain linearization schemes will be provided in the guidelines.

The work to be compiled in these guidelines is described in Appendix J, which includes a schedule for the preparation of this guideline set.

WBS 3.4 Diffraction Theory for Large Structural Members. Considerable diffraction theory research has been conducted in recent years by the offshore petroleum industry and by government agencies. The bulk of this work has been directed toward the analysis of large gravity-base oil production structures in the North Sea and ship motion analysis. More recently, diffraction analysis has been employed for the feasibility studies and preliminary design analysis of tension leg platforms and semi-submersible drilling rigs. The Navy needs to maintain current knowledge of the SOA developments in this technology field. A set of definitive design guidelines is required to accomplish the objective. These design guidelines must address in detail the eight level 3 research tasks identified under the level 2 "Diffraction" topic of Figure 11.

These guidelines must also describe and summarize the one semi-empirical and five analytical diffraction theory problem solution techniques identified in Figure 12. Specific attention will be given to the boundary integral and finite element solutions via the eigenfunction expansion of the Green's function. The description of the boundary integral forms of the diffraction solution will address both the explicit and approximate form of the Green's function. Computationally expedient forms of the diffraction theory solution, such as those for separable geometries, axisymmetric geometries, and two-dimensional geometries, will be described. A comparison of the linear frequency domain and nonlinear time domain solutions will be provided with a description of the effects of random wave loading. Current NAVFAC/NCEL mooring and drift force research should be incorporated into the guidelines with other SOA developments. The effects of finite free surface displacement

in the linear solution will be assessed as will the wave slamming topic for large body members. Viscous effects are generally small in the diffraction analysis regime but may have important local significance. This and other energy dissipation topics, such as radiated wave making, will be described in detail.

As before, each task-specific guideline will be prepared by an expert in the field. Each guideline will include a summary of pertinent previous research and experimental results. A detailed description of the work to be compiled in each guideline and a schedule are provided in Appendix K.

WBS 3.5 Combined Morison Equation and Diffraction Analysis for Composite Structures. A number of currently deployed and proposed ocean structures are composed of neither entirely large body or small body members but, rather, a composite of both. The problem is further complicated because the large body or small body categorization is relative to the wavelength. That is, in mild seas with small wave periods (and hence short wavelengths) the structural members may be entirely within the diffraction regime. However, for storm conditions where a number of high period (long wavelength) waves may be present, the analysis range for the structural members may be fully distributed over the drag dominated, mixed dominance, inertially dominated, and diffraction regimes. It is inappropriate to model such a structure using entirely diffraction theory or a pure Morison equation approach since a large number of errors may be introduced by improper modeling of inertial and viscous effects.

Consequently, techniques combining Morison equation and diffraction theory problem solutions have evolved to analyze these structures. Generally speaking, the diffraction solution is obtained first since the presence of the large bodies alters the wave field. Once the velocity potential solutions for the incident and scattered potentials are obtained, the local kinematics required for the Morison equation analysis of the small body members can be computed.

For floating bodies, the solution becomes more complicated since the dynamic response of the structure is a function of the diffraction and the Morison equation hydrodynamic loading. Transcendentally, the Morison equation loading is a function of the dynamic response in the hydroelastic sense. The problem becomes even more complex when nonlinear mooring analysis is addressed since this also affects the dynamic response of the structure. Iterative techniques can be used to solve this problem with successive refinements in the accuracy. Simultaneous fluid/structure/mooring interaction solutions are also being developed.

A set of comprehensive definitive design guidelines are required to incorporate this technology into Naval design and analysis capabilities. These design guidelines must specifically address the level 3 tasks identified in Figure 11. As described above, the various modeling techniques, both iterative and single pass, should be identified as well as their accuracies and computational efficiencies. The effects of mooring systems, interference effects between large and small body members, and wave slamming on composite structures must be included in the guidelines. The selection of Morison equation force coefficients for the hydroelastic application in which translation as well as rotation occurs must also be specified in the guidelines. Interactive effects

between viscous and radiated wave making damping should be identified for the single pass fluid/structure/mooring simultaneous solutions as well as the iterative techniques.

Again, each task-specific guideline will be prepared by an expert for that particular topic. This expert will be intimately familiar with the pertinent previous research and will summarize existing experimental results. The work to be compiled for each guideline is described in detail in Appendix L, which includes a work schedule.

WBS 3.6 Risk Analysis. The Navy's ocean structures are unique in their mission requirements and frequently in their structural geometries. Each design must be approached with regard to the proposed mission. The purpose, longevity, payload, motion constraints, and other factors can be expected to vary considerably from design to design. This is only partially true for the offshore petroleum industry since many of their requirements are somewhat standardized from design to design. Personnel safety is of primary concern for the offshore petroleum industry since up to 100 crew members populate a structure. In addition, the monetary value of the drilling and at-sea production systems may equal or exceed the cost of the structure itself. Finally, environmental factors and loss of oil revenues from a structural failure further affect risk analysis.

A design guideline which assesses the risk and economic, political, and national security repercussions of a structural failure should be compiled for probable Navy structures. Depending upon the results of this risk analysis, the Navy may not be justified in designing structures to the same rigorous standards as the petroleum industry. This design guideline for risk analysis should be compiled by Naval personnel familiar with ocean engineering technology, Naval program requirements, and multiple parameter probability theory. These design guidelines should be compiled to aid the design engineer or a government contract technical representative with the choice of analysis techniques and safety factors in order to obtain a structure proportionately balanced in terms of both risk and capital investment.

WBS 4.0 Project Management

This category provides for those general management functions included in the development of the wave force project plans.

WBS 4.1 Development Plan. This task provides for the development of the project plan. Based on a review of efforts and recommendations from WBS 1.0, high-payoff technology topics germane to Navy requirements have been identified and integrated into a project plan (Ref 6).

NAVFAC/NCEL is not exclusively developing wave forces technology. Industry (particularly the oil industry) and other governmental organizations are also active in developing this technology. This task provides for assimilating available information on external wave force developments, as described in the WBS 1.5 of this report.

Development of wave forces technology within the entire ocean engineering community is very active and dynamic. As a result, periodic review, evaluation, and updating of the development plan is necessary. This task provides for updating the project plan; this document is an update of the initial project plan (Ref 6).

WBS 4.2 Project Integration. This task provides for the integration and coordination of wave force developments. Specifically, continuous review of on-going efforts is made. Developments which impact the NAVFAC/NCEL program or show great promise of success are integrated into this wave force project to the maximum extent possible.

In addition, this task provides for the close coordination of efforts within this project to insure compatibility of the results of one task to the needs of another. For example, the force coefficients developed in WBS 2.1.2 will be compatible with the kinematic predictive techniques developed in WBS 2.2.

CONCLUSIONS AND RECOMMENDATIONS

This report provides a description of the NAVFAC/NCEL Wave Forces research program to date and a proposal that a comprehensive set of design guidelines be compiled which document the existing state-of-the-art and standard-operating procedures for wave force design methodology. The report was initiated with a review of previous and proposed Navy ocean structures. The review demonstrated that Navy requirements encompass a broad spectrum of ocean facilities ranging from bottom-fixed lattice structures to moored deformable floating bladders. The deficiencies in Navy capabilities to predict wave and current induced hydrodynamic loads have been identified for each of the example ocean facilities reviewed. In general, these deficiencies have led to overly conservative designs and/or the need for costly and extensive model studies.

To mitigate these deficiencies the NAVFAC/NCEL Wave Forces research program was initiated in 1979. Figure 13 shows the completed and proposed research efforts associated with this program versus fiscal year. Figure 14 shows the same information in a logic network format. As evident in Figure 13 and as described within this report, the work has been divided into four categories: requirements definition, design procedure development, wave force design guidelines, and project management.

The initial efforts were conducted to define the Navy wave forces technology requirements. This was accomplished via an NCEL workshop of noted wave forces experts, an assessment of the Morison equation wave force prediction technique by an experienced offshore engineering firm and reviews of the technical literature. These comprehensive reviews led to the preparation of the initial project development plan (Ref 6) which proposed research and development be conducted regarding Morison equation type force models and the kinematics prediction theories necessary for the use of the Morison equation. These specific research activities were identified because they had a high probability of improving the accuracy of wave force predictions for proposed Navy structures.

As indicated in Figure 13, the proposed research was conducted as part of the WBS 2.0 Design Procedure Development category. The force model research involved the extension of the conventional Morison equation by the addition of two more terms, development of a set of drag and inertia coefficients for combined wave and current flow fields and the development of a wave force data base from a large scale experiment. The kinematics research involved a small scale feasibility study to develop experimental procedures to measure water particle velocities in combined wave and current flow fields. This study demonstrated that

laboratory facilities to conduct larger experiments (to obtain a combined wave/current kinematics data base) were not available and, as described within this report, this effort was deleted.

Since only a small number of the Morison equation force and kinematics topics could be actively researched and since no diffraction theory topics were addressed, this report has proposed that a comprehensive set of design guidelines be compiled which summarizes the research described above and existing state-of-the-art and standard-operating-procedure wave force design methodology. As shown in Figures 13 and 14, six design guideline subjects have been recommended; i.e., Morison equation force coefficient selection, Morison equation deterministic static analysis, Morison equation random dynamic analysis, diffraction theory analysis, combined diffraction theory and Morison equation analysis, and risk analysis for Navy structures. Each of these six subjects has been subdivided into a number of related topics. As described in this report, each of these topics will be a summary of existing technology and will be compiled by an expert in that specific topic area. A summary of the recommended topics for each of the six guidelines is provided as follows (also see Figure 11):

Morison Equation (Drag and Intertia) Force Coefficient Selection: This recommended design guideline summarizes existing technology relative to the selection of drag and inertia coefficients for use in the Morison equation. The topics described below have been identified to enhance the design engineer's ability to select force coefficients for the various design conditions encountered:

(1) Review of previous experimental results for C_d and C_m and perform a dimensional analysis to establish the parametric dependency of the coefficients.

(2) Comparison of C_d and C_m values for laboratory versus field experiments to ascertain whether laboratory coefficients can be extrapolated to the ocean environment.

(3) Review of the variation in C_d and C_m between those experiments that have employed measured kinematics and those that used theoretical (wave theory) kinematics in the regression analysis solutions for the coefficients.

(4) Effects of artifical (laboratory) and real ocean marine growth roughness on C_d and C_m.

(5) Effects of transverse forces (lift) on the (in-line) force coefficients.

(6) Effects of member orientation (vertical, inclined, horizontal) on C_d and C_m.

(7) Effects of combined current and/or structural motion and waves on C_d and C_m.

Morison Equation Deterministic Static Analysis. This recommended design guideline summarizes the various forms of the Morison equation for modeling wave forces under a variety of deterministic static design conditions. The following topics are recommended:

(1) Review of the various force models versus necessary kinematics models and versus compatible force coefficient set requirements.

(2) Force models for combined wave-current and/or structural motion conditions.

(3) Force models for different member orientations (vertical, inclined, horizontal).

(4) Wave slamming force models for static analysis force applications.

(5) Force models for determining static transverse (lift) forces.

(6) Effects of mutual interference between adjacent and contiguous members on static force predictions.

(7) Free surface corrections to Morison equation static force predictions for members at or near the free surface.

Morison Equation Random Dynamic Analysis. This recommended design guideline summarizes Morison equation wave force technology for small member structures which respond dynamically to nonperiodic (random) hydrodynamic loading. The following topics are recommended:

(1) The probabilistic and statistical models necessary for description of random processes such as the 3-D ocean surface and induced hydrodynamic loads.

(2) The effects of directional spectra and spreading on the computation of random wave forces.

(3) The use of extreme value statistical techniques for the extrapolation of rare events from limited existing statistical data bases.

(4) Revise the breaking wave case stream function tables for use in nonlinear time domain analyses.

(5) Morison equation force coefficients for use in random dynamic force predictions.

(6) The effects of combined waves and currents on random dynamic force predictions.

(7) Wave slamming models for use in a random dynamic force analysis.

(8) Random dynamic analysis techniques in the frequency domain.

(9) Random dynamic analysis techniques in the time domain.

Diffraction Theory Analysis. This recommended design guideline summarizes diffraction analysis technology for structures whose width dimensions are large relative to the incident wavelength (i.e., the structure is so large it that modifies, or diffracts, the incident wave field). The following topics are recommended:

(1) The various linear frequency domain diffraction theory analysis techniques.

(2) Nonlinear time domain diffraction theory analysis techniques.

(3) The effects of linearized and nonlinear mooring forces on structural response.

(4) The effects of drift forces.

(5) The effects of random waves on diffraction theory wave force predictions.

(6) Free surface correction procedure for linearized diffraction theory solutions.

(7) The effects of viscous and radiation damping on diffraction theory wave force predictions.

(8) The effects of wave slamming for large diffraction theory members.

Combined Morison Equation and Diffraction Analysis for Composite Structures. This recommended design guideline summarizes the wave force prediction techniques for composite large and small member structures. The following topics are recommended:

(1) The pressure and kinematics field modifications.

(2) The selection of force coefficients for the relative motion Morison equation portion of the composite analysis.

(3) The effects of mutual interference between the large and small members.

(4) Mooring effects for composite structures.

(5) Wave slamming effects for composite structures.

(6) Viscous and radiation damping effects for composite structures.

Risk Analysis. This recommended design guideline summarizes risk assessment techniques tailored for Navy applications. Individual topics are not identified for this design guideline since they will depend specifically on the force error estimates from the other five guidelines. Consequently this task must be initiated after the completion of the other five guidelines.

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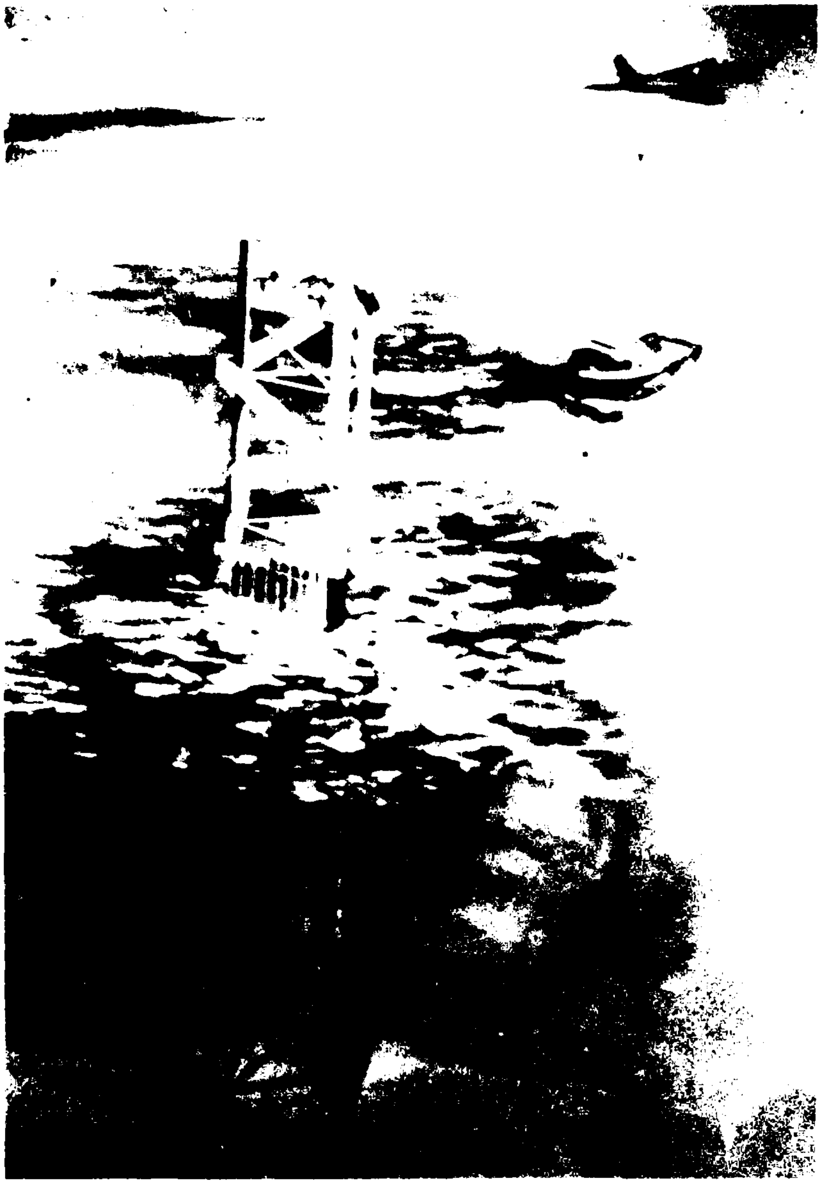


Figure 1. Example of a bottom-fixed lattice structure

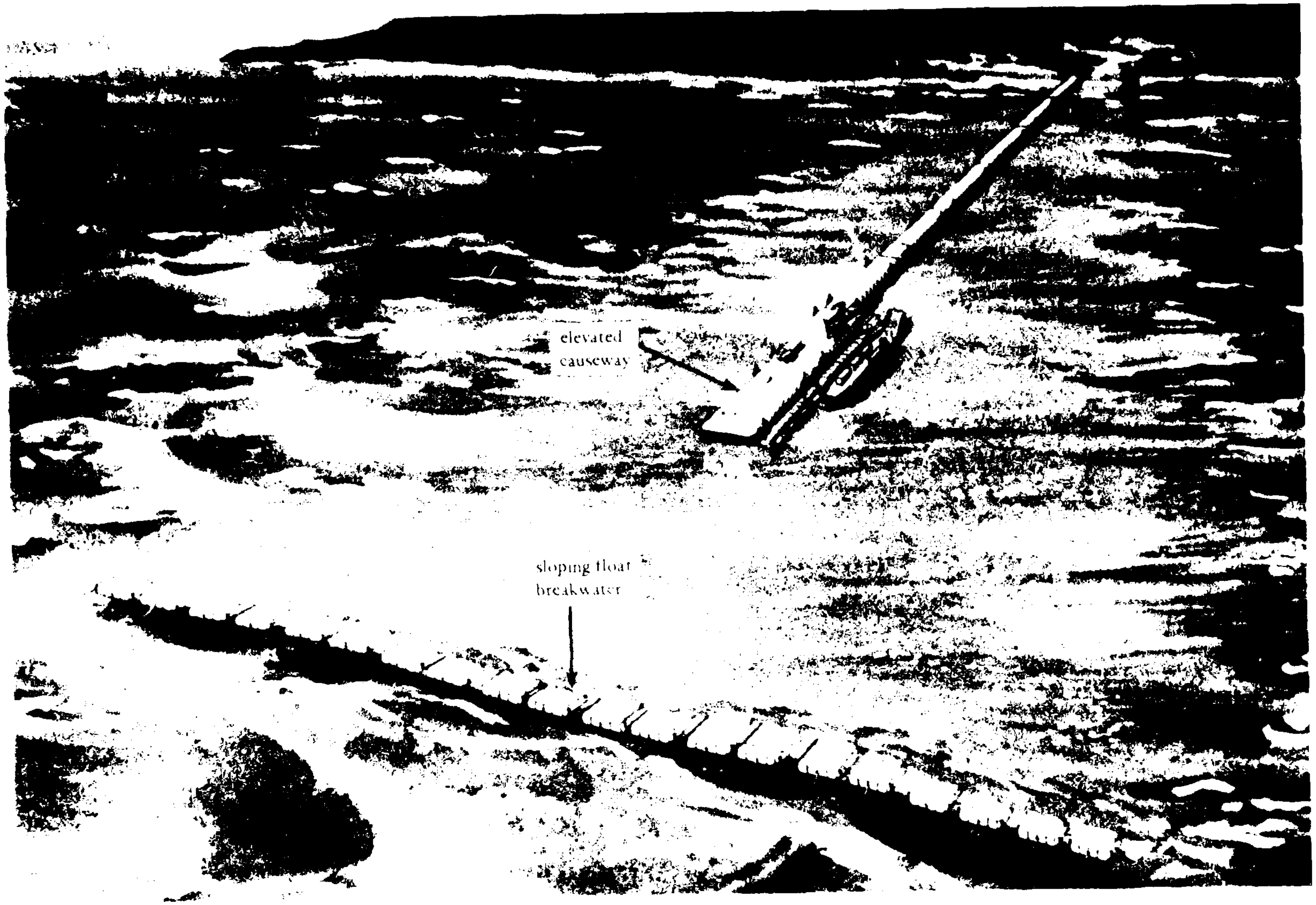


Figure 2. Floating breakwater application.

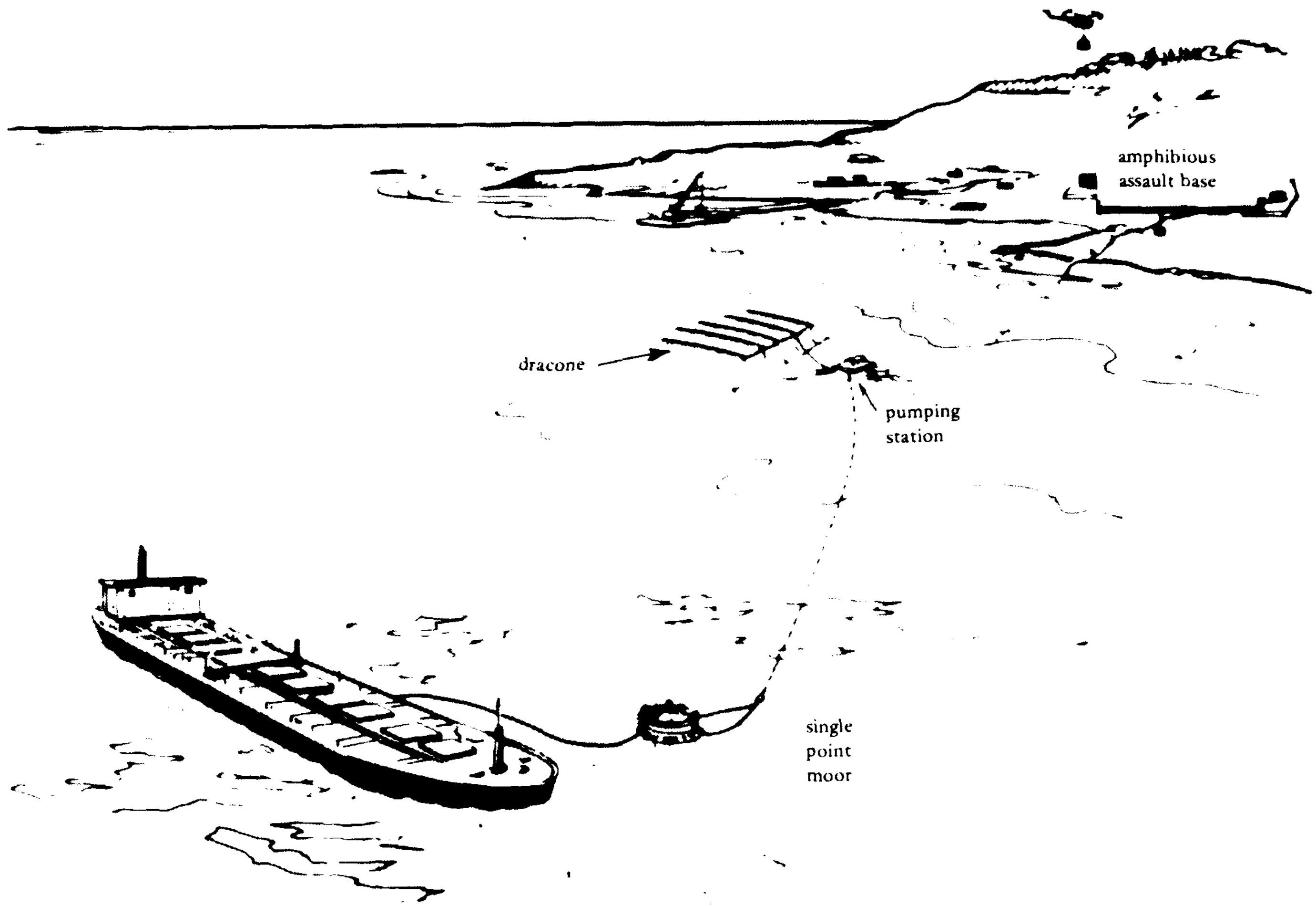


Figure 3. Offshore bulk fuel system.

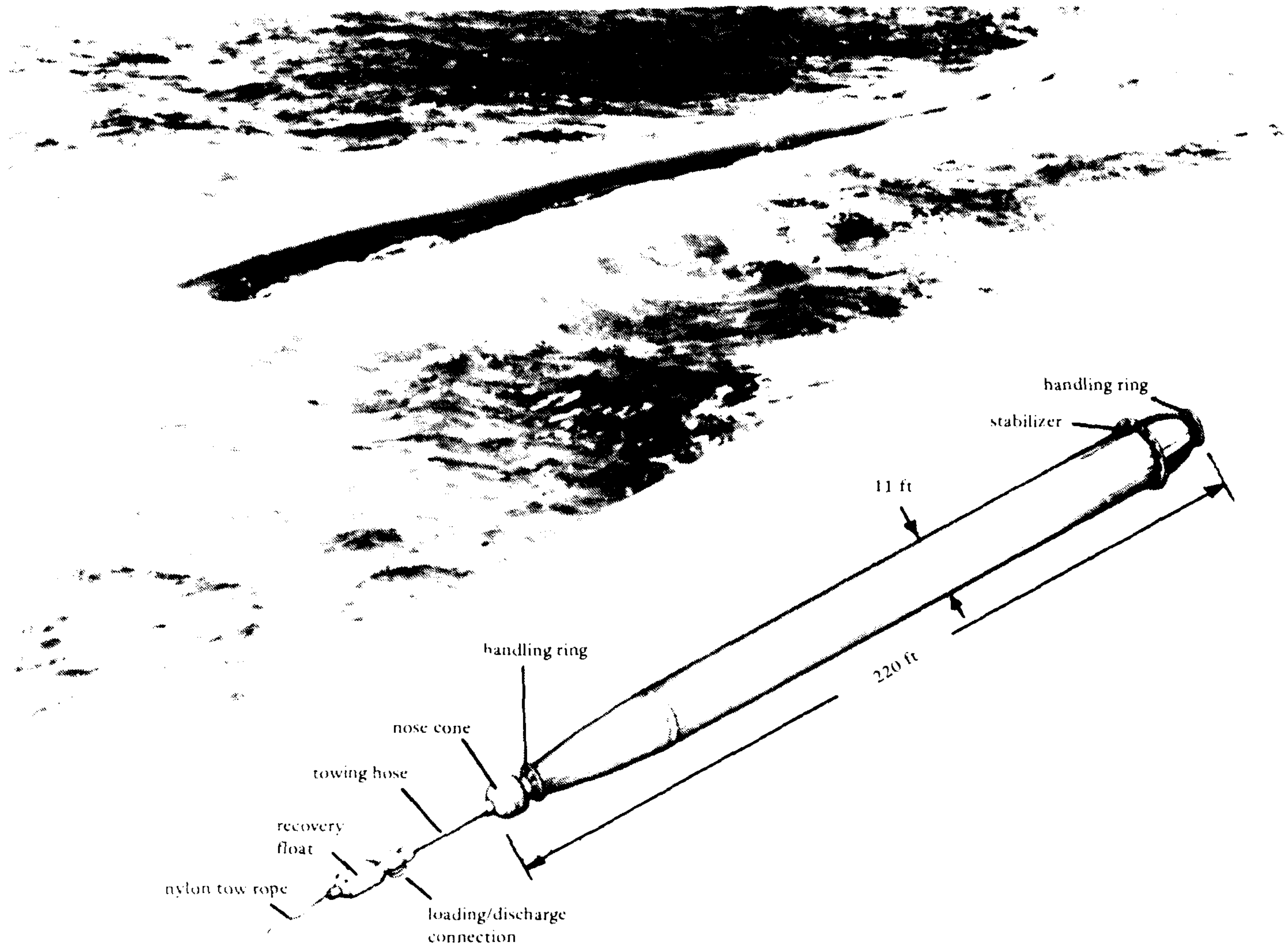


Figure 4. Type I. dracone: 135,000-gal capacity.

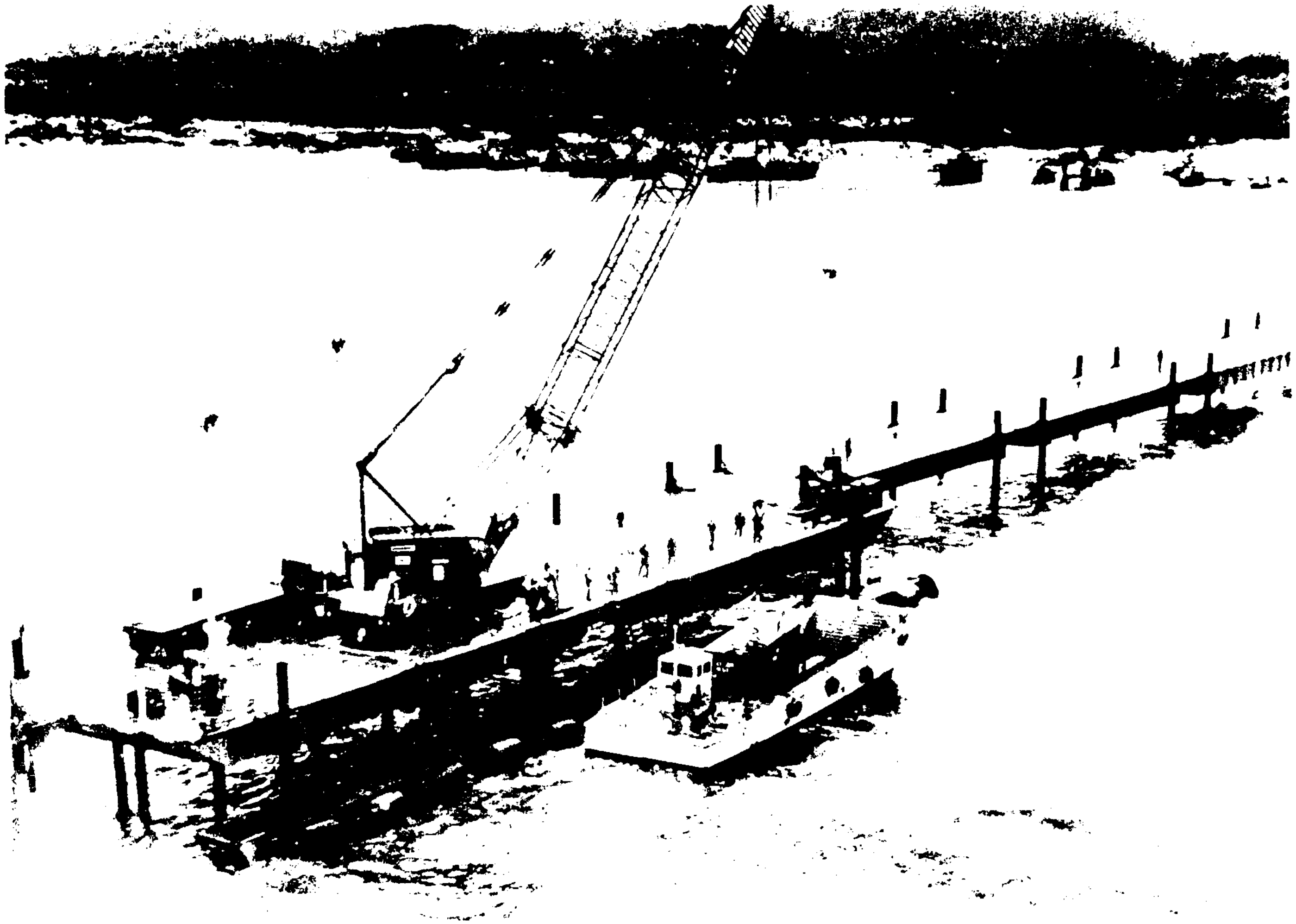


Figure 5. Elevated causeway

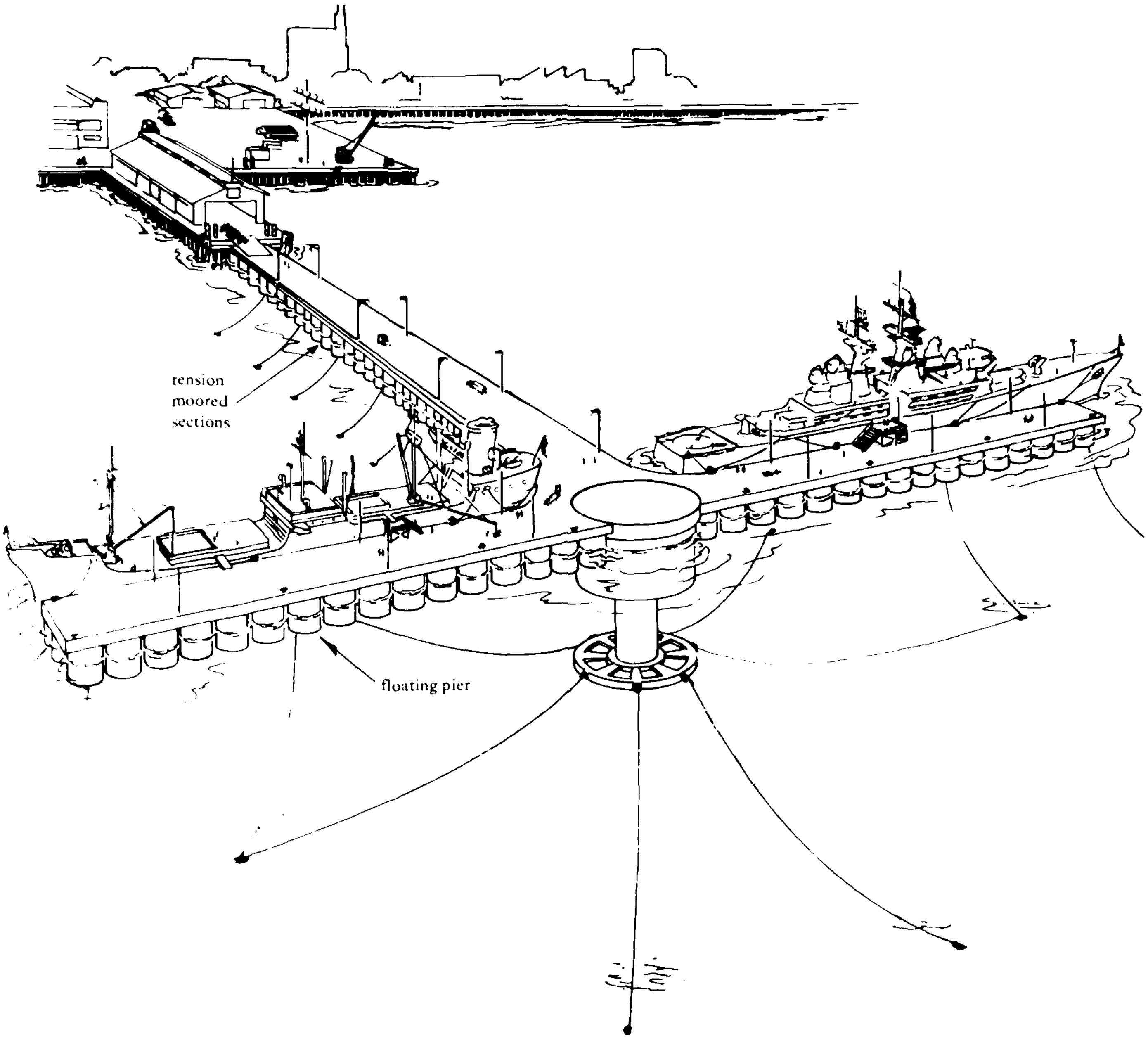


Figure 6. Open-sea pier facility.

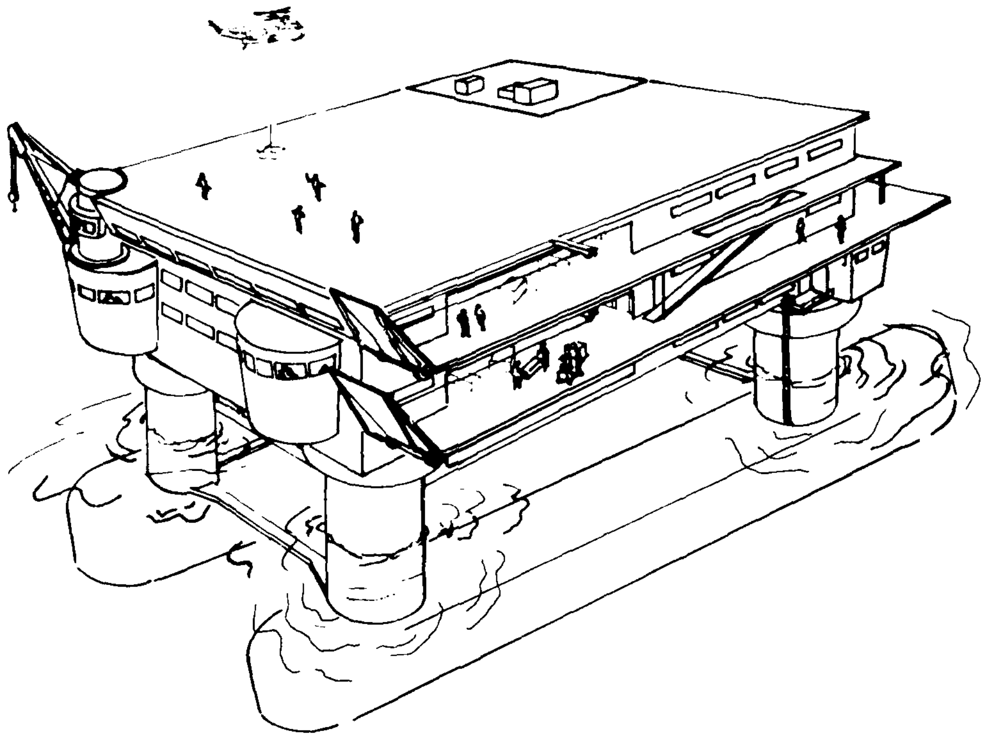


Figure 7. Large dimension logistic platform.

Figure 8. Damaged split-pipe protected marine cable.

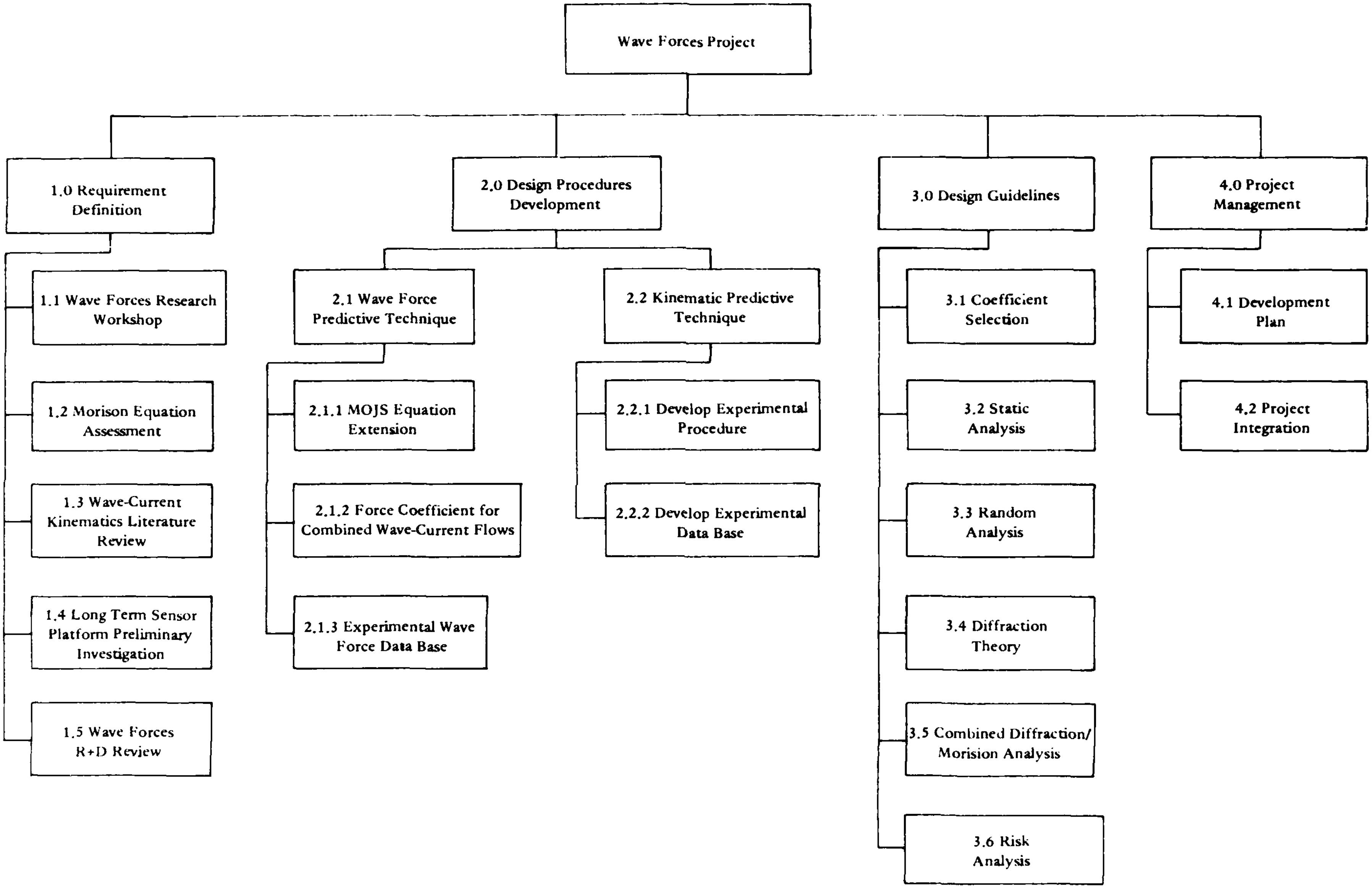


Figure 9. Wave forces project work breakdown structure (WBS).

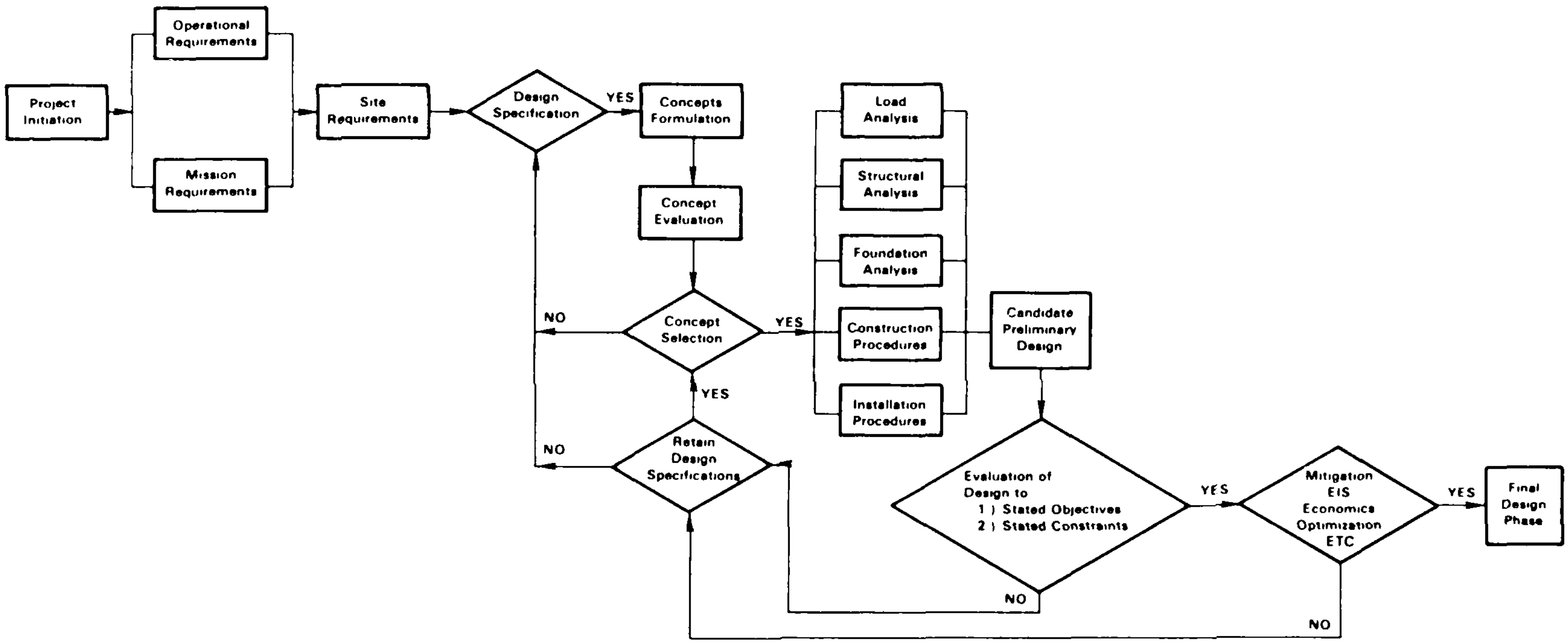


Figure 10. Design process methodology.

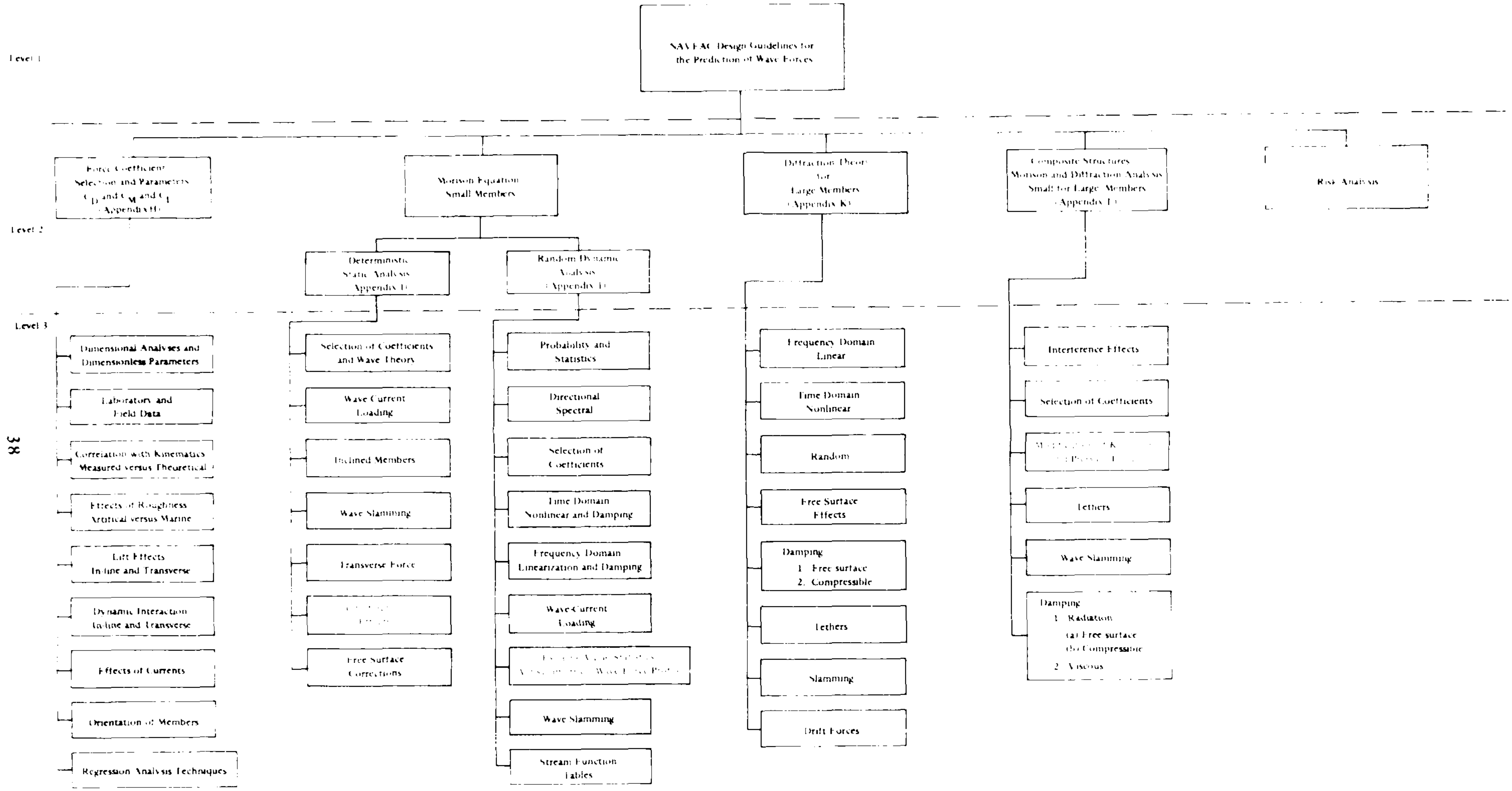
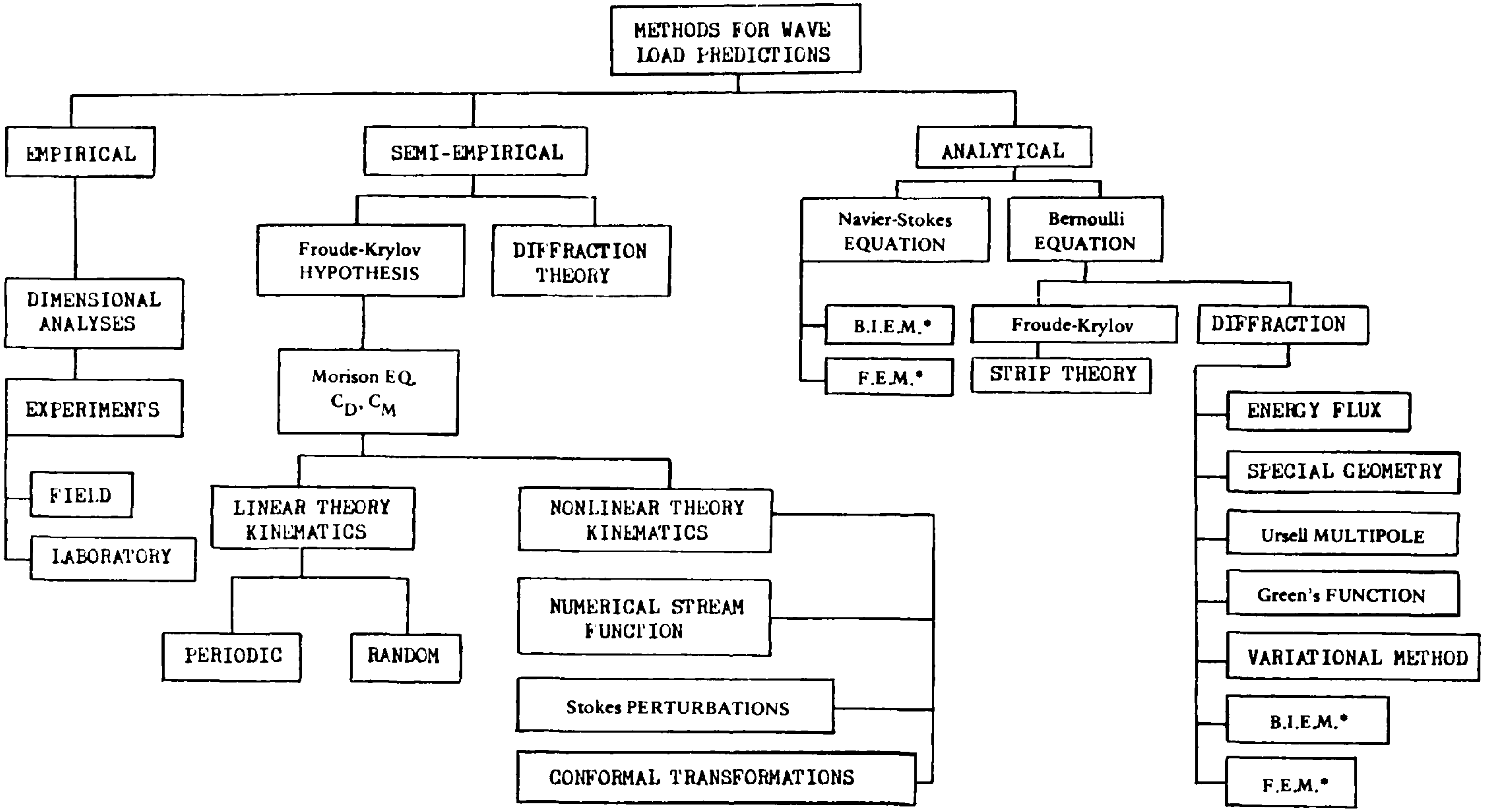


Figure 11. NAVFAC wave forces design guidelines.



*Boundary Integral Element Method

*Finite Element Method

Figure 12. Load prediction methods for non-breaking waves (Ref 19).

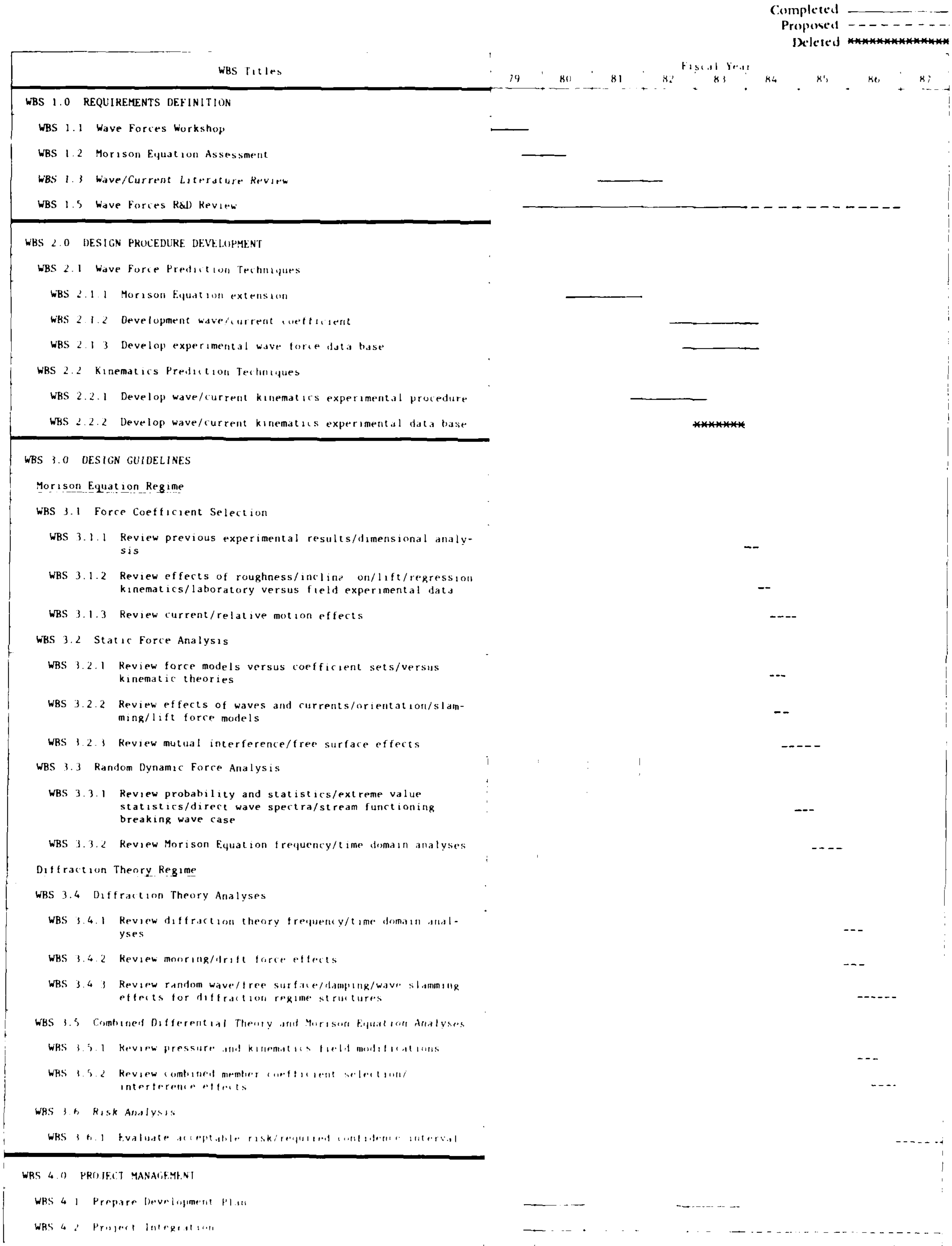


Figure 13. Wave forces project schedule.

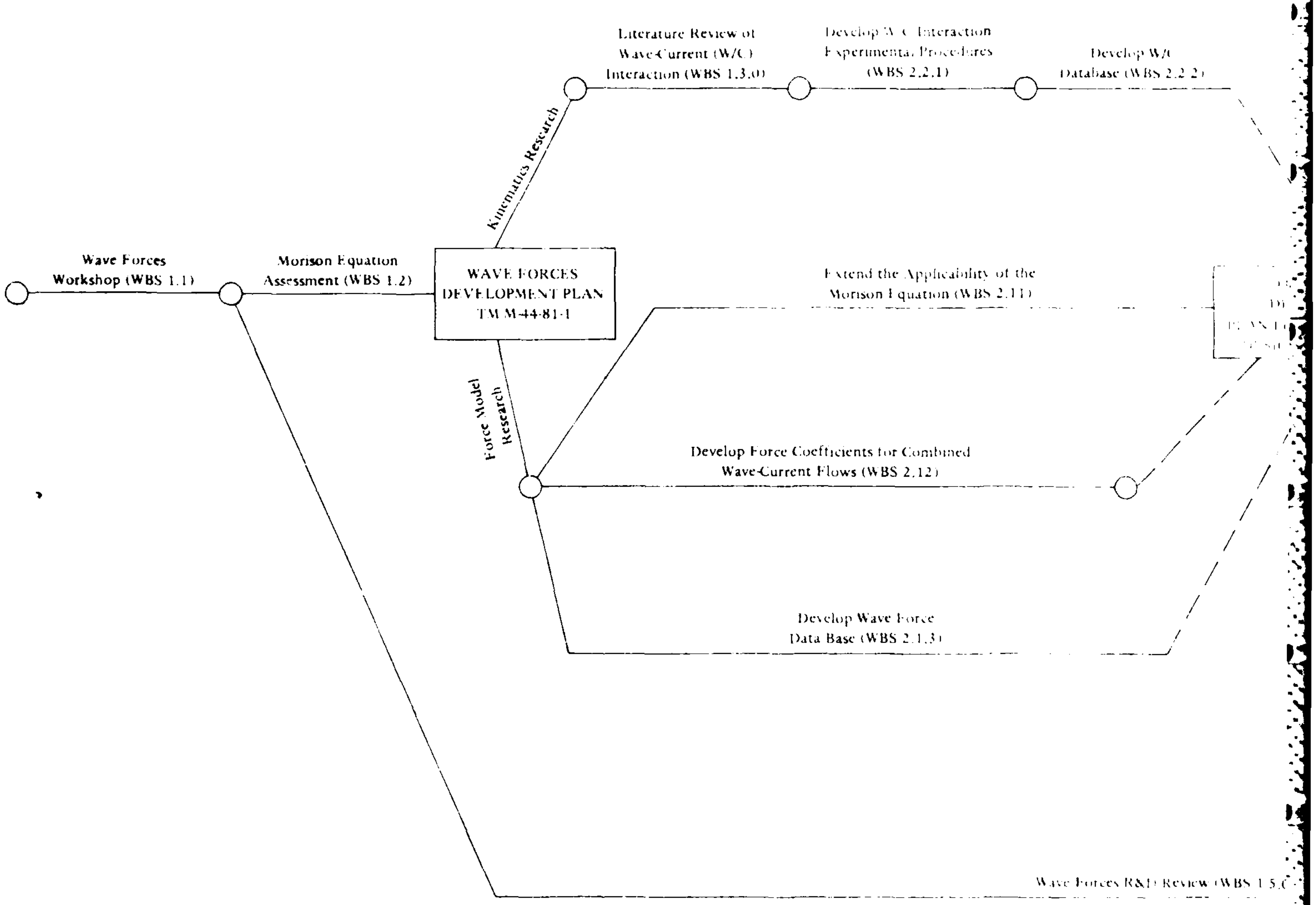
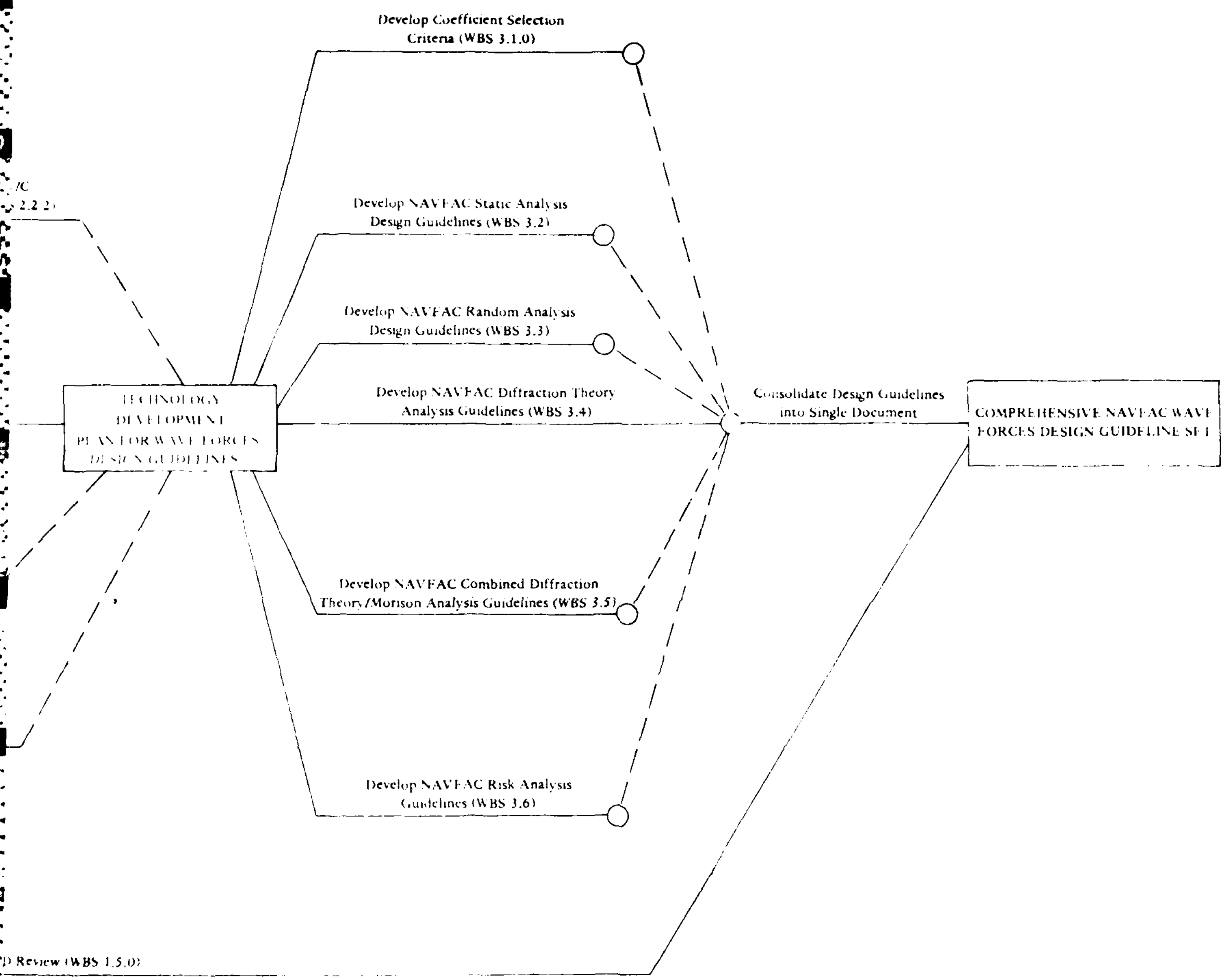


Figure 14. Logic network for the



network for the wave forces project.

Appendix A

WBS 1.1 RESEARCH WORKSHOP ON ENVIRONMENTAL LOADS ON FIXED OFFSHORE STRUCTURES

Dates: 19 and 20 April 1979

Location: Naval Civil Engineering Laboratory
Port Hueneme, CA 93043

Coordinator: Thomas M. Ward, Code L44

Attendees:

1. Robert G. Dean, Professor; University of Delaware
2. W. (Mike) Kim, Ph D; NAVFACENGCOM, Code 0453B
3. Bruce J. Muga, Professor; Duke University
4. William J. Nordell, Ph D; Director, Ocean Structures Division, NCEL
5. Anatol Roshko, Professor; California Institute of Technology
6. Turgut Sarpkaya, Professor; Naval Postgraduate School
7. Robert N. Sorensen, Ph D; Coastal Engineering Research Center
8. Thomas M. Ward; Ocean Structures Division, NCEL

AGENDA:

1. Background: Review "Ocean Facilities Exploratory Development" block program plan.

2. Scope: Environmental loads include hydrostatic, wave, wind, and ice, but exclude earthquake. Structures are bottom fixed or tethered and of a type likely to be erected for the U.S. Navy.

3. Review "Wave Forces on Ocean Structures" Work Unit Plan: A brief review of the current work unit plan.

4. Typical Structures: Review the types of offshore structures likely to be erected for the U.S. Navy.

5. Results: Discuss the final results or "product" of this project. Should it be in the form of a requirement specification, a regulation, a design guide, a revision to DM-26, a separate and exhaustive design guide?

6. Technology Assessment:

(1) Availability of environmental data

(2) Wave forecast and hindcast techniques

(3) Wave particle kinematics

(4) Wave loading on vertical columns (Morison Equation)

(5) Wave slamming loads on horizontal surfaces

(6) Wave forces on groups of columns

(7) C_D values for two- and three-dimensional bodies

(8) C_m values for two- and three-dimensional bodies

(9) Effect of marine growth

(10) Wind loading

(11) Ice loading

(12) Hydroelastic dynamics

(13) Large structures and diffraction theory

(14) Structural design/analysis techniques

(15) Shear-flow effects

(16) Combined wave-current loading (Expand on previous "Morison" discussion)

7. Identification of Research Projects: From the above inventory of problem areas, select research projects which provide a high pay-off in terms of enhancing NAVFAC's ability to perform its mission.

RECOMMENDATIONS:

1. Purchase EXXON "Offshore Test Structure" (OTS) data for analysis by Naval personnel

2. Determine the reliability of the "Design Wave" procedure using EXXON-OTS data

3. Determine the accuracy of "Design Wave" kinematics as compared with ocean wave data from EXXON-OTS and other field measurements

4. Develop a nonlinear random diffraction theory

5. Develop a free-surface correction procedure for the Morison equation

6. Perform laboratory scale experimental verifications of wave kinematics and dynamics

7. Determine the effect of a current on wave kinematics and dynamics (without free surface)

8. Perform experimental verifications of wave theories in a laboratory and in the ocean

9. Revise the Dean Stream Function table Case D, "F eaking Waves," using the Chaplin stream function algorithm

10. Prepare a design manual for offshore structures (viz. DM-XX)

11. Develop a method for the analysis of wave-structure interaction of flexible elastic structures

12. Determine the parametric dependence of forces on multiple pile groups in waves

13. Develop analytical models for computing wave slamming forces on cylinders

14. Develop analytical models for computing hydroelastic oscillations of structures subject to wave action

15. Develop criteria for establishing deck elevation for a dry deck versus sea state

16. Prepare a design manual for floating structures at zero Froude Number (viz. DM-xxx)

Appendix B

WBS 1.2 ASSESSMENT OF THE MORISON EQUATION (Ref 7)

Reference 7 identified three major task areas that would enhance the NAVFAC capability to predict wave forces. These three task areas are subdivided into subjects (arabic numbers) and topics pertinent to each subject in the tabular summary provided below. A graphical depiction of this tabular summary is also provided in Figure B-1.

Reference 7 also provided information regarding the transition from research activities to design procedure. Figure B-2 shows this transition relative to SOA developments and design SOP used in engineering analyses. This information was provided as guidance for the WBS 1.0 Requirements Defintion Activities and WBS 4.0 Project Management Efforts in order to delineate a comprehensive step-wise continuous research program.

In addition Reference 7 also described the various wave force modeling regimes and provided a summary of suggested force coefficient values for use in static-equipment Morison equation loading analyses. This information is provided in Figures B-3 and B-4, respectively.

TASK No. I: Improving and Extending the Morison Equation

1. Better characterization of wave forces on single structural members

    a. Surface roughness
    b. Noncircular cylindrical sections
    c. Vortex-induced lift forces
    d. Near-surface wave slamming
    e. Near-surface cyclic buoyancy
    f. Inclined members
    g. Vibrating and compliant structure motions

2. Better characterization of complex assemblages of structural members

    a. Mutual interference of conglomeration of multiple members
    b. Surface roughness
    c. Noncircular cylindrical sections
    d. Vortex-induced lift forces
    e. Near-surface wave slamming
    f. Near-surface cyclic buoyancy
    g. Inclined members
    h. Vibrating and compliant structure motions

3. Temporal characterization of wave forces

   a. Time and spatial variations of fluid flow conditions
   b. Variations of force coefficients throughout wave cycle
   c. Fluid-structure dynamic response

4. Spectral characterization of wave forces

   a. Spectral wave force dynamic analysis
   b. Spectral wave force fatigue analysis
   c. Directional wave force spectra analysis
   d. Nonlinear response

5. Probabilistic characterization of wave forces

   a. Statistical descriptions of wave force parameters
   b. Directional wave spreading descriptions
   c. Joint probability distribution descriptions

6. Better quantification of force coefficients

   a. Force coefficients for complex hydrodynamic and structural geometric conditions
   b. Force coefficients for large Reynolds number range
   c. Force coefficients for different wave force analysis approaches
   d. Systematic distillation of existing wave force data

TASK No. II: Improve the Description of Ocean Kinematics

1. Better characterization of the wave field

   a. Velocities and accelerations
   b. Kinematics of breaking waves
   c. Nonlinear wave-current interactions
   d. Short-crested and directional waves

2. Better characterization of water column motions

   a. Ocean current and current profile
   b. Effects of density stratification
   c. Effects of internal waves

3. Interaction Effects

   a. Nonlinear interactions of relative motions
   b. Boundary layer interactions

TASK No. III: Fluid-Structure Interaction

1: Fundamental fluid force phenomenon in periodic flow

a. Fluid memory

i. boundary layer
ii. time dependent wake description for oscillating flows

b. Mathematical fluid dynamics

i. fluid behavior
ii. kinematics
iii. dynamics

2. Basic analysis of wave forces on ocean structures

a. Reformulation of fundamental momentum equations for fluid dynamics
b. Numerical solutions of inertial pressure concept (IPC) and vortex transport integral (VTI) concept

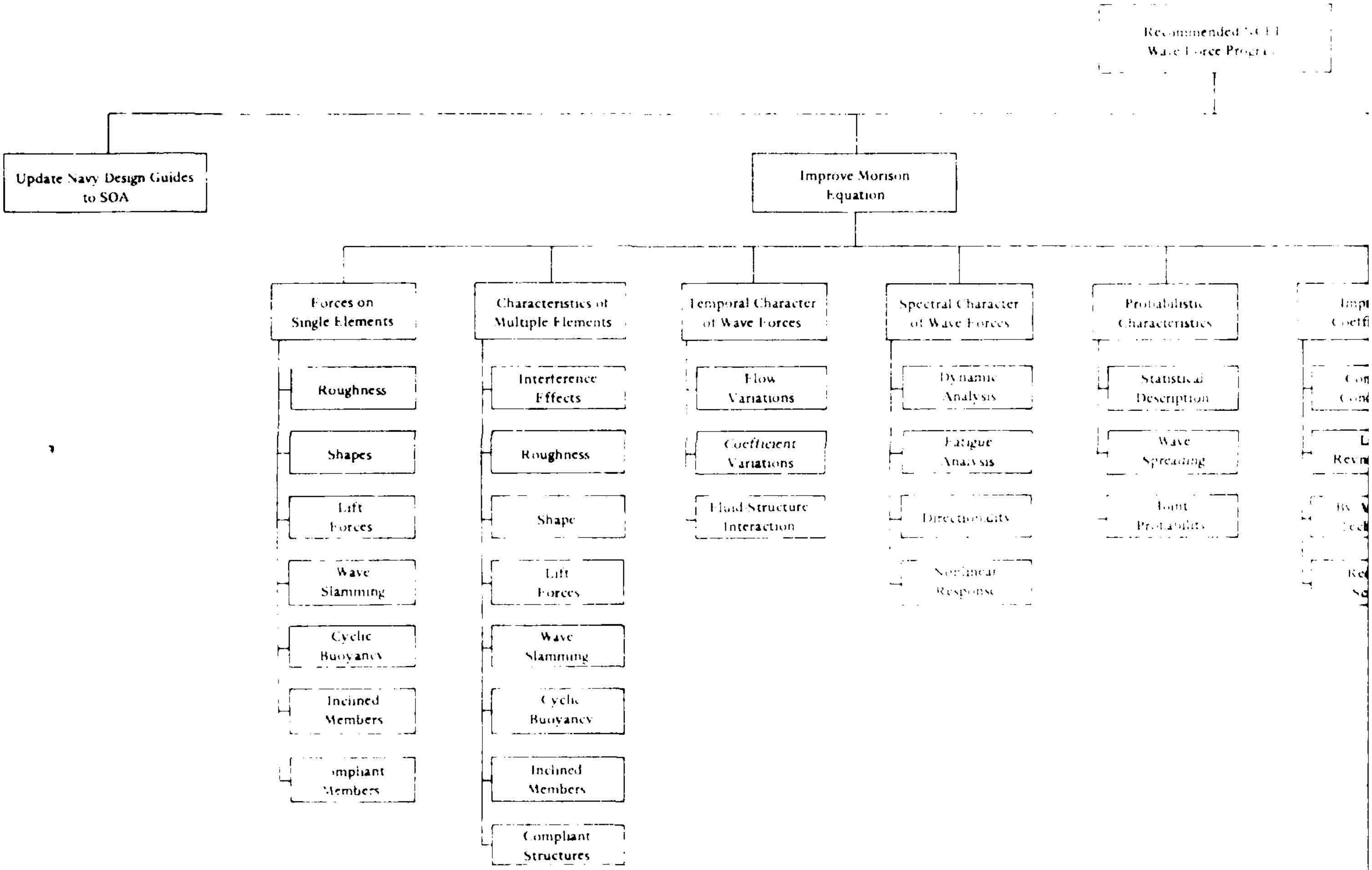
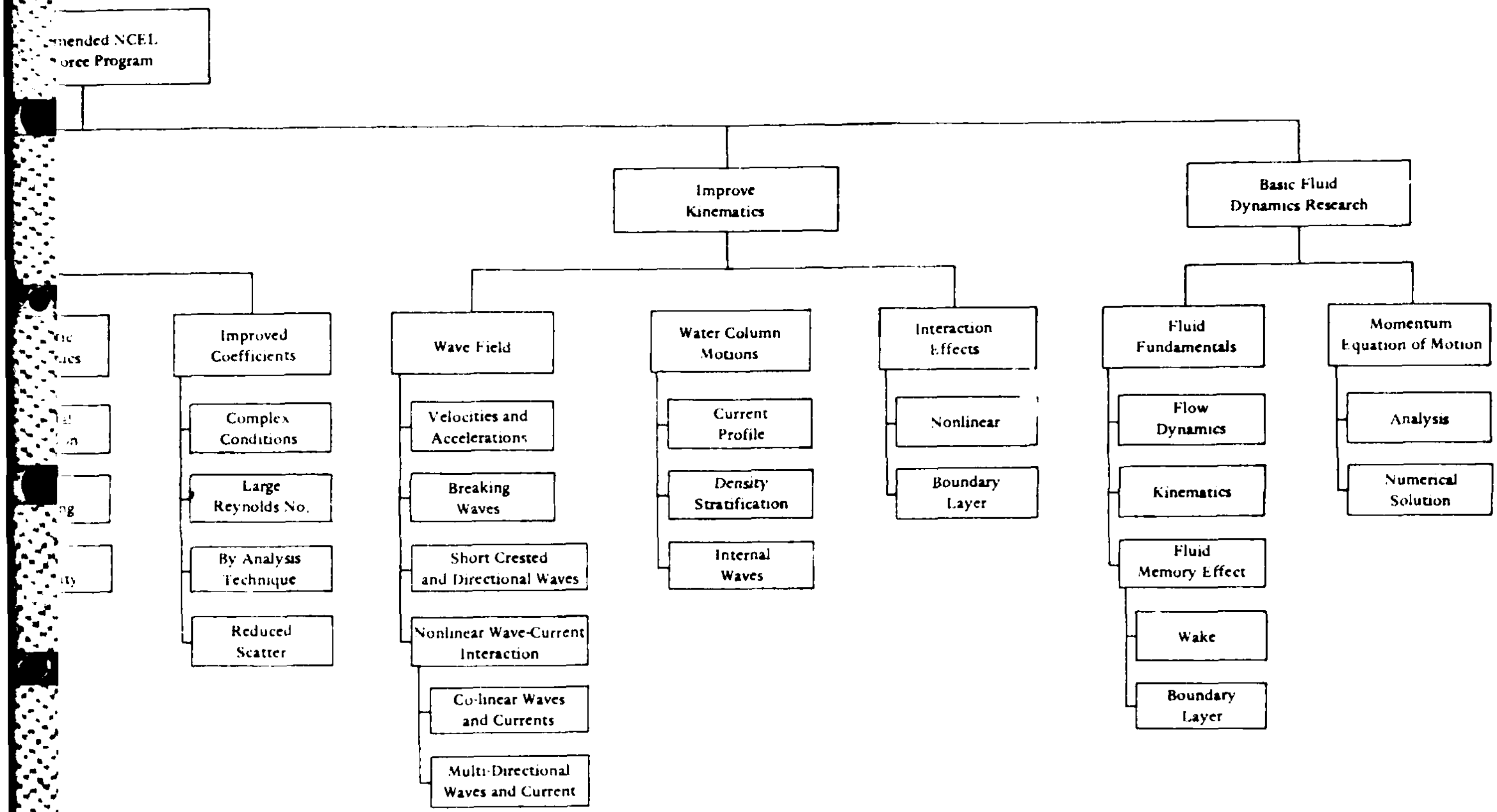


Figure B-1. WBS 1.2 requirements definition for Mori



definition for Morison equation force modeling.

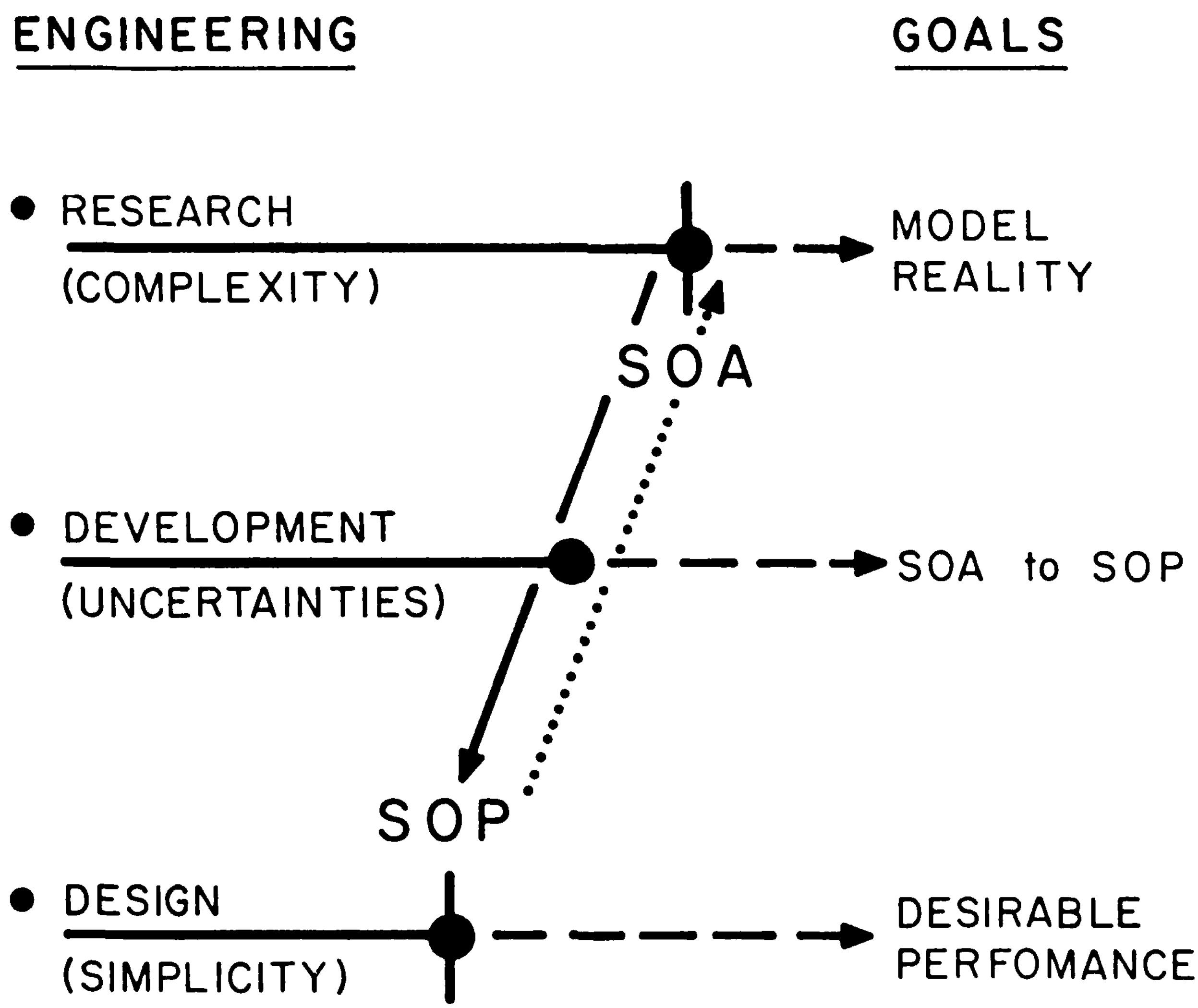
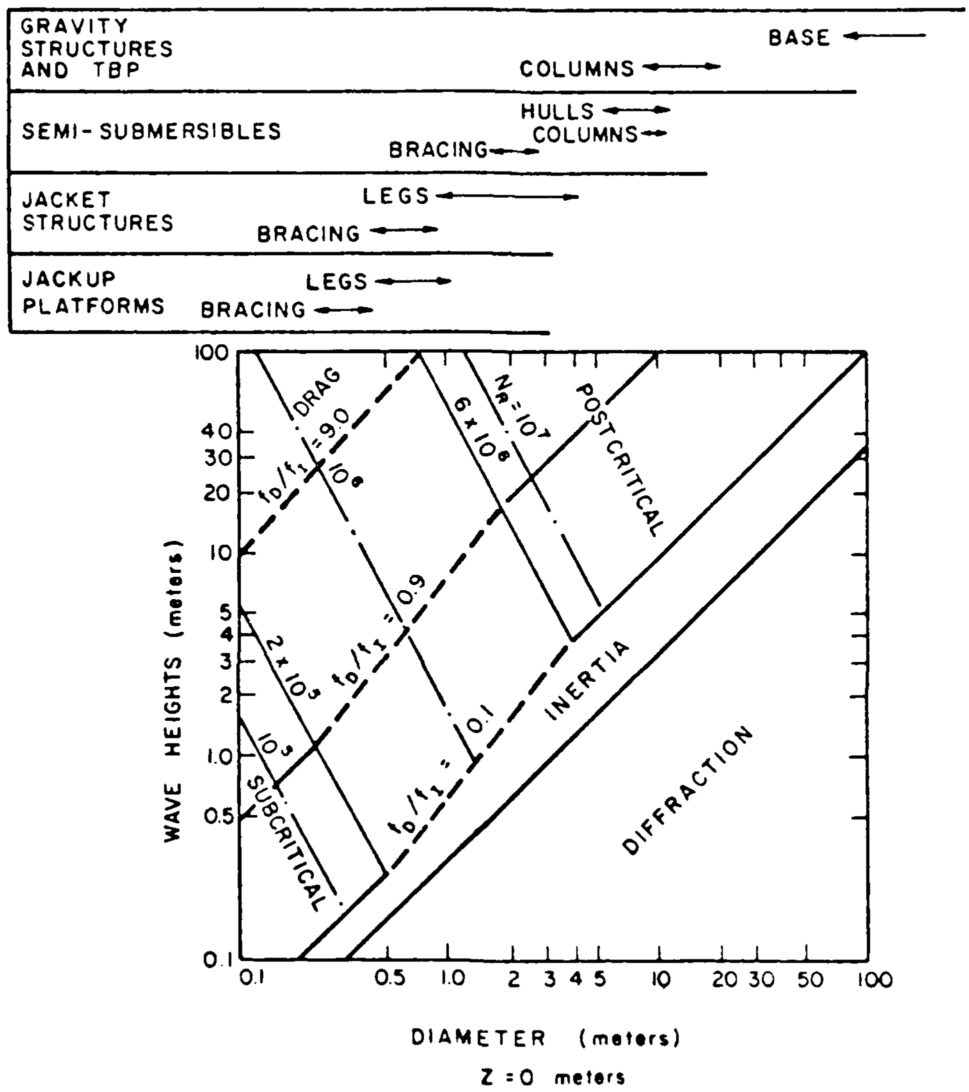


Figure B-2. General forms of research activities (Ref 7).



TBP: Tethered buoyant platform referred to in this report as tensioned leg platform

f_D - drag force

f_I - inertial force

N_R - Reynolds no.

Figure B-3. Comparative importance of different loads for different wave and member geometries (adapted from Ref 24 and appearing in Ref 7).

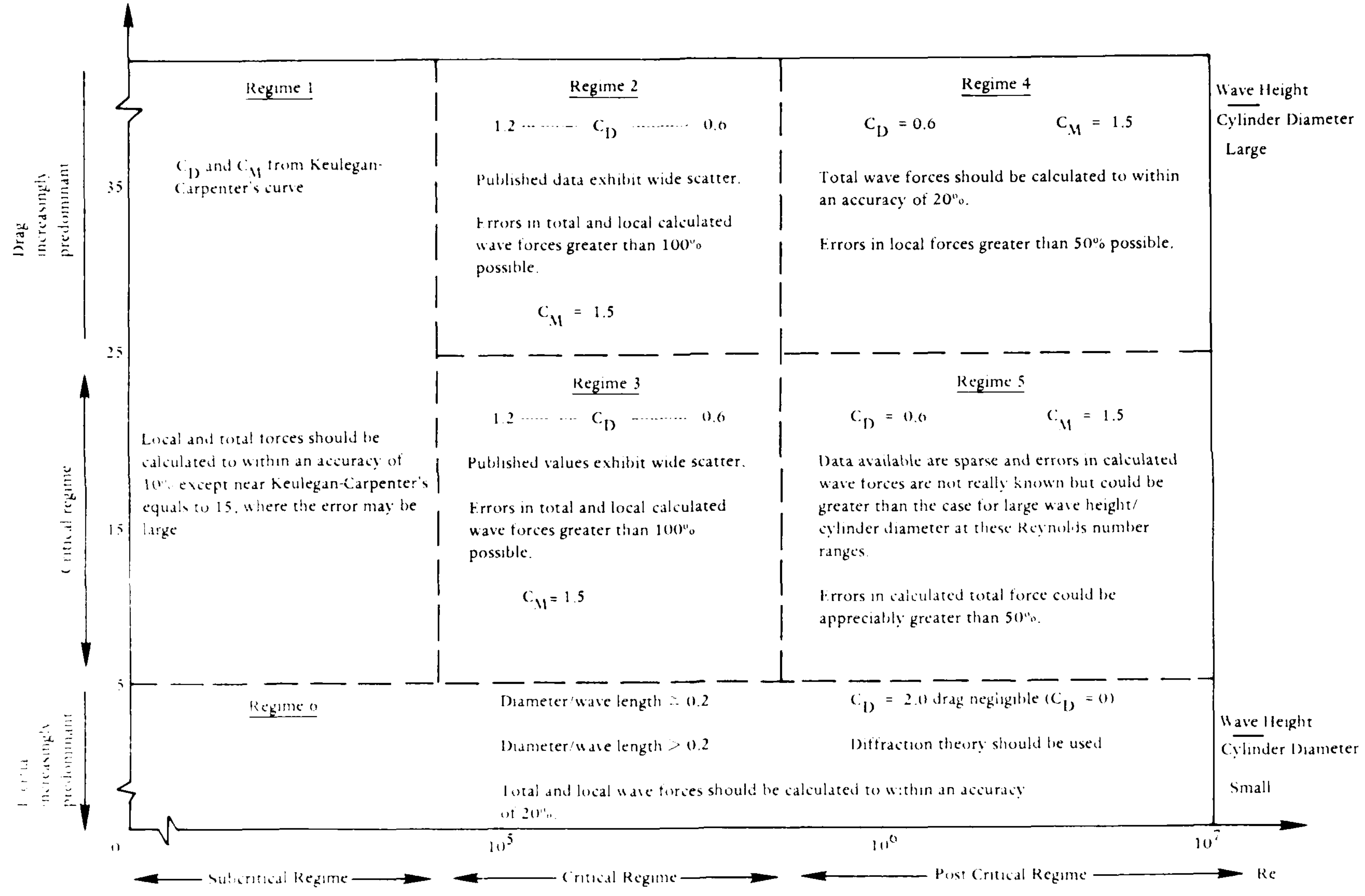


Figure B-4 Summary of suggested values of C_D and C_M as functions of Reynolds number and Keulegan-Carpenter number for smooth, vertical surface piercing circular cylinders (adapted from Ref 25)

Appendix C

WBS 1.3 EXCERPTS FROM A REVIEW OF CERTAIN ASPECTS OF WATER WAVE-CURRENT INTERACTIONS*

*Reference 8.

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5.	A Review of Experimental Equipment	19
6.	Recommendations for Future Study	26
	APPENDIX A: A Detailed Review of Papers	29
A.1	Thomas, G. P., "Wave-Current Interactions: An Experimental and Numerical Study. Part 1: Linear Waves," JFM, vol, 110, 1981	30
A.2	Iwagaki, Y. and Asano, T., "Water Particle Velocity in Wave-Current System," Coastal Engineering in Japan, vol. 23, 1980	35
A.3	van Hoften, J.D.A. and Karaki, S., "Interaction of Waves and a Turbulent Current," Proc. 15th ICCE,* 1976	45
A.4	Bakker, W. T. and van Doorn, T. "Near Bottom Velocities in Waves With a Current," Publication No. 208, Delft Hydraulics Laboratory, December 1980	57
A.5	Francis, J.R.D. and Dudgeon, C. R., "An Experimental Study of Wind-Generated Waves on a Water Current," Quart. J. Royal Meteorological Society, 93, 1967	66
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A.7	Kato, H. and Tsuruya, H., "Experimental Study of Wind Waves Generated on Currents," Proc. 16th ICCE, 1978	77
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*Note abbreviation ICCE is International Conference on Coastal Engineering.

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1. Introduction

The subject of water wave-current interactions is important in many different types of engineering problems. An interest in the overall effect on waves of large scale currents in their ability to refract waves has been the subject of much recent research; see, e.g., Jonsson et al. (1970). Currents can inhibit or promote wave breaking, and indeed may change patterns of local nearshore sediment transport by waves. For example, the discharge of large volumes of heated water from coastal sited power plants has the potential to induce patterns of large-scale offshore currents that may alter the nearshore mean velocity field. The interaction of the normal wave activity with these currents can change both the location and the direction of wave breaking at the shore and thereby affect the littoral transport of local sediments.

Another type of problem where wave-current interaction may be important relates to wave related forces on offshore structures. This has several different aspects ranging from the detailed fluid mechanics of the fluid-structure interaction to the interpretation of ocean wave measurements as a guide to design. The latter problem is described by Dalrymple (1973) where forces are measured on offshore structures and then gross coefficients such as the coefficients of drag or virtual mass are to be inferred from these measurements. However, without an adequate description of the velocity and acceleration field such interpretations are difficult.

The purpose of this literature survey is to review various aspects of current-wave interactions as they relate to the details of the hydrodynamics problem. The large body of literature dealing with theoretical aspects will not be reviewed; there is an excellent review paper by Peregrine (1976) which devotes itself primarily to this with a host of theoretical papers reviewed....

This review is directed toward the literature which deals with experimental investigations of wave-current interactions and related problems. Of course, theoretical and experimental aspects of such a problem cannot be separated effectively so that some attention will indeed by devoted to the former; however, as stated, the primary goal is to define the state-of-the-art of experiments related to current-wave interactions. An important consideration connected with this is a review of experimental equipment used for such studies and the synthesis from that review of the important characteristics of a reliable laboratory facility for use specifically in wave-current studies. Included in this review is a discussion of the importance of scale considerations in experimental investigations.

This report is assembled in a somewhat unique manner. In the first portion there will be a review of important facets of the theoretical problem, if only to form a fundamental foundation. A summary of the important papers will then be presented with detailed summaries and pertinent figures presented.... This latter summary provides data for the reader to review in detail to form his own opinion of the content of the various papers. From this survey certain recommendations for future study are made along with a description of the important aspects of the

experimental equipment and the suggested directions of a wave-current study to result in an understanding of the kinematic characteristics of wave-current interactions.

Appendix D

WBS 1.4 and 4.1 SUMMARY OF PROPOSED WAVE FORCE TECHNOLOGY DEVELOPMENT TOPICS

TECHNOLOGY DEVELOPMENT TOPICS FROM REFERENCE 5

No.	Topics

1. Site Analysis

   a. Model site specification

2. Loads Analysis

   a. Forces on moored platforms
   b. Forces on fixed platforms
   c. Extreme wave characteristics
   d. Extreme wind loads
   e. Vortex effects in oscillating flow

3. Structures

   a. Sensor platform parametric design investigation
   b. Survivability in extreme seas
   c. Finite amplitude rigid-body dynamics

4. Foundations and Moorings

   a. Mooring component development
   b. Geotechnical classification system
   c. Scour, slumping, and soil stability
   d. Rock and coral anchoring
   e. Dynamics of marine soils

5. Installation Operations and Procedures

   a. Ocean construction and deployment manual
   b. Underwater maintenance and repair
   c. Motion compensation and load handling techniques
   d. Real time monitoring of ocean engineering operations

TECHNOLOGY DEVELOPMENT TOPICS FROM REFERENCE 6

No.	Topics
1.	Determine the accuracy of "Design Wave" kinematics compared to ocean wave data from EXXON-OTS and other field measurements
2.	Develop a nonlinear random diffraction theory
3.	Develop a free-surface correction procedure for the Morison equation
4.	Perform laboratory scale experimental verifications of wave kinematics and dynamics
5.	Determine the effect of a current on wave kinematics and dynamics (without free surface)
6.	Perform experimental verifications of wave theories in a laboratory and in the ocean
7.	Revise the Dean Stream Function table Case D, "Breaking Waves," using the Fenton stream function algorithm
8.	Develop a method for the analysis of wave-structure interaction of flexible elastic structures
9.	Determine the parametric dependence of forces on multiple pile groups in waves
10.	Develop analytical models for computing wave slamming forces on cylinders
11.	Develop analytical models for computing hydroelastic oscillations of structures subject to wave action
12.	Develop criteria for establishing deck elevation for a dry deck versus sea state
13.	Publish Ocean Engineering Environmental Data Source Book
14.	Marine growth study
15.	Improve the Morison equation
16.	Evaluate the Morison equation coefficients statistically
17.	Determine ocean engineering environmental data requirements

No.	Topics
18.	Determine design guidelines and experimental values of C_d and C_m for combined body-body interactions
19.	Determine design guidelines and experimental values of C_d and C_m for three-dimensional bodies
20.	Design-sea loading sensitivity analysis program
21.	Evaluation of wave force and hindcasting techniques
22.	Evaluate methods for prediction of wind-driven currents
23.	Determine free surface effects on surface piercing structures
24.	Determine effect of wind-driven water loading
25.	Determine second-order wave effects in shallow water
26.	Perform measurements and develop kinematic theory for shear flow waves
27.	Determine effect of wave loading on membrane structures

Appendix E

WBS 2.1.1 MORISON'S EQUATION AND WAVE FORCES ON OFFSHORE STRUCTURES*

6.6 Method No. 6 - Analysis of the Residue

As noted earlier, Keulegan and Carpenter expressed the time-dependent force as...

$$2\,F/(\rho D U_m^2) \;=\; (\pi^2/K)\,C_m \sin\theta - C_d\left|\cos\theta\right|\cos\theta + \Delta R \qquad (59)$$

where ΔR represents the residue given by

$$\Delta R \;=\; C_3\cos(3\,\theta - \phi_3) + C_5\cos(5\theta - \phi_5) + \ldots \qquad (60)$$

Keulegan and Carpenter considered only the first term in Eq. (60) in the form

$$\Delta R \;=\; A_3\sin 3\theta + B_3\cos 3\theta \qquad (61)$$

and evaluated A_3 and B_3, and showed that they are functions of K, within the range of their K and Re values ($3 < K < 120$ and $5700 < Re < 29300$). Keulegan and Carpenter noted that "for period parameters, K, in the neighborhood of the critical, $U_mT/D = 15$, the representation of forces is more exact by using Eq. (59) together with Eq. (61). They did not pursue the matter further.

The obvious disadvantage of this expanded form of the MOJS equation [Eqs. (50) and (61)] is that it now requires the evaluation of four coefficients, *namely* C_d, C_m, *and either* C_3 *and* ϕ_3 *or* A_3 *and* B_3. *Even* then the calculated and measured forces do not always correspond partly due to the existence of other harmonics and partly due to the pronounced effect of the randomness of the shedding, spanwise coherence, and the motion of a few vortices, vice large number of vortices. This, in turn, requires the addition of two more terms involving C_5 and ϕ_5. Clearly, the determination of the dependence of six coefficients on the parameters characterizing the phenomenon is a nearly impossible task and is not very practicable for the design of offshore structures, even if one were to confine his attention to smooth circular cylinders alone! It is partly because of this reason and partly because of the uncertainties in the input parameters (velocities and accelerations) that the two-term MOJS equation has been used over the past thirty years in spite of its known limitations (at least under laboratory conditions). The inaccuracies resulting from the use of the said equation have been compensated partly by the mitigating effects of the ocean environment (reduced spanwise

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*Excerpts from Reference 11, reprinted as presented in the original.

coherence, omnidirectionality of the waves and currents distribute the residue over a broad band of frequencies, making the predictions of the MOJS equation come closer to those measured) and partly by the designer *through the use of hidden and intentional safety factors.*

In view of the foregoing it was decided to explore the possibility of revising the MOJS equation with the following constraints: (a) the revision should be fluid-mechanically meaningful; (b) the revised form of the equation should contain no more than the two coefficients already in use, namely, C_d and C_m; (c) the coefficients of the additional terms should be related to C_d and C_m (since they too are functions of K, Re, and k/D) through a careful spectral and Fourier analysis of the residues; and (d) the revised form of the equation should reduce to the MOJS equation in the drag and inertia dominated regimes.

***

It is thus apparent that the MOJS equation must be modified to minimize the residue and that this modification should involve the third and the fifth harmonics. It is with this realization that the MOJS equation was written as a sum of Equations (50) and (60) as

$$2F/(\rho D U_m^2) = (\pi^2/K) C_m \sin\theta - C_d |\cos\theta| \cos\theta$$

$$+ C_3 \cos(3\theta - \phi_3) + C_5 \cos(5\theta - \phi_5) \qquad (62)$$

Then the attention has been concentrated on the determination of C_3, ϕ_3, C_5, and ϕ_5 with the constraints cited earlier. This, in turn, required an extensive search for a functional relationship between the said coefficients and the known parameters C_d, C_m, K, Re, and k/D.

***

The data used in the present analysis also have shown that C_3, ϕ_3, C_5, and ϕ_5 depend on K, Re, and k/D. Note that K, Re, and k/D are the same independent parameters which determine the Fourier-averaged values of C_d and C_m, as shown clearly by Sarpkaya.... Detailed study of the said four coefficients have shown that it is preferable to explore their dependence on K, C_d, and C_m *rather than on K, Re, and k/D.* Evidently, the two approaches are mathematically identical. Thus, one has

$$C_i = C_i(K, C_d, C_m), \qquad i = 3, 5 \qquad (63a)$$

$$\phi_i = \phi_i(K, C_d, C_m), \qquad i = 3, 5 \qquad (63b)$$

By virtue of Eqs. (63a) and (63b), the residue is solely dependent on K, C_d, and C_m. Significant effort has been devoted to determining the form of the above relationships by numerous correlations. Here only the final result and not the year-long efforts will be described.

It is a well-known fact that in harmonic flow the ratio of the maximum inertia force to the maximum drag force is given by the MOJS equation as $\pi^2 C_m/KC_d$. Thus, the ratio of the deviation of the maximum inertial force from its ideal value to the maximum drag force is proportional to

$$\Lambda = (2 - C_m)/(KC_d) \tag{64}$$

It must be noted in passing that C_m exceeds its ideal potential-flow value for small values of K and β, as noted earlier in connection with the discussion of Stokes solution. However, in the region of K values from about 8 to 20, this increase is not of special importance and the ideal value of C_m for a circular cylinder may be taken equal to 2. For other shapes of bodies Λ may be written as

$$\Lambda = (C_m^* - C_m)/(KC_d) \tag{65}$$

where C_m^* is the ideal value of the inertia coefficient for the particular body.

It is clear that Λ approaches zero for both the small and large values of K and is unique for a given K, Re, and k/D. Thus, unique relationships should exist between the coefficients C_i, ϕ_i, and Λ and K. Numerous attempts have shown that $C_i\sqrt{\Lambda}$, and $\phi_i\sqrt{\Lambda}$ are indeed unique functions of K for all smooth and rough cylinders (within the range of data and the experimental scatter).

***

The following simple distribution has been chosen to relate $C_3\sqrt{\Lambda}$, ..., $\phi_5\sqrt{\Lambda}$ and K

$$M_p = A_{mp} + B_{mp}\, e^{C_{mp}(K - 12.5)^2} \tag{66}$$

in which M denotes either $C\sqrt{\Lambda}$ or $\phi\sqrt{\Lambda}$; p, the index 3 or 5; and A_{mp}, B_{mp}, and C_{mp}, three constants for the relationships between $M_p\sqrt{\Lambda}$ and K. A parametric analysis of these coefficients for the best fit of the predictions of Eq. (66) to the experimental data has shown that

$$\begin{array}{lll} A_{c3} = 0.01 & B_{c3} = 0.10 & C_{c3} = -0.08 \\ A_{\phi 3} = -0.05 & B_{\phi 3} = -0.35 & C_{\phi 3} = -0.04 \\ A_{c5} = 0.0025 & B_{c5} = 0.053 & C_{c5} = -0.06 \\ A_{\phi 5} = 0.25 & B_{\phi 5} = 0.60 & C_{\phi 5} = -0.02 \end{array} \tag{67}$$

These are considered as universal constants and are not dependent on K, Re, and k/D for a circular cylinder.

The four-term MOJS equation may now be written as

$$2\,F/(\rho D U_m^2) = (\pi^2/K)C_m \sin\theta - C_d|\cos\theta|\cos\theta$$

$$+ \Lambda^{-1/2}\left|A_{c3}+B_{c3}\exp[C_{c3}(K-12.5)^2]\right|$$

$$\cdot \cos\left\{3\theta - \Lambda^{-1/2}\left\{A_{\phi 3} + B_{\phi 3}\exp[C_{\phi 3}(K-12.5)^2]\right\}\right\}$$

$$+ \Lambda^{-1/2}\left\{A_{c5} + B_{c5}\exp[C_{c5}(K-12.5)^2]\right\}\cos\left\{5\theta - \Lambda^{-1/2}\left\{A_{\phi 5}\right.\right.$$

$$\left.\left. + B_{\phi 5}\exp[C_{\phi 5}(K-12.5)^2]\right\}\right\} \quad (68)$$

*** ...Eq. (68) reduces to the two-term MOJS equation for all practical purposes outside the drag-inertia dominated regime. The additional terms cause an amplitude and frequency modulation in the in-line force, in a manner similar to that provided by Eq. (58), and reflect the role played by the growth and motion of vortices on the in-line force.

6.6.1 The Predictions of the New MOJS Equation

...The original MOJS equation...is called "the two-term MOJS equation." The one obtained with the addition of only $C_3\cos(3\theta-\phi_3)$ is called "the three-term MOJS equation," i.e.,

$$2\,F/(\rho D U_m^2) = (\pi^2/K)C_m\sin\theta - C_d\left|\cos\theta\right|\cos\theta$$

$$+ \Lambda^{-1/2}\;0.01 + 0.10\,e^{-0.08(K-12.5)^2}$$

$$\cdot \cos\left\{3\theta + \Lambda^{-1/2}\left\{0.05\right.\right.$$

$$\left.\left. + 0.35\,e^{-0.04(K-12.5)^2}\right\}\right\} \quad (69)$$

Finally, the one obtained with the addition of $[C_3\cos(3\theta-\phi_3)+C_5\cos(5\theta-\phi_5)]$ is called "the four-term MOJS equation" [Eq. (60)] or more specifically,

$$2F/(\rho D U_m^2) = (\pi^2/K)C_m\sin\theta - C_d\left|\cos\theta\right|\cos\theta$$

$$+ \Lambda^{-1/2}[0.01 + 0.10\,e^{-0.08(K-12.5)^2}]\cos\left\{3\theta\right.$$

$$\left. + \Lambda^{-1/2}[0.05 + 0.35\,e^{-0.04(K-12.5)^2}]\right\}$$

$$+ \Lambda^{-1/2}[0.0025 + 0.053\,e^{-0.06(K-12.5)^2}]$$

$$\cdot \cos\left\{5\theta - \Lambda^{-1/2}[0.25 + 0.60e^{-0.02(K-12.5)^2}]\right\} \quad (70)$$

***

8.0 RECOMMENDATIONS

1. Extensive research is needed to justify each and every generalization of the original MOJS equation. Specifically, laboratory and ocean experiments are required to determine (a) the kinematics of the wave and current interactions, (b) the wave and current induced forces on smooth and rough circular cylinders, (c) the forces acting on yawed cylinders and the merits of the "independence principle," and (d) to examine critically the generalization of the MOJS equation to the prediction of the dynamic response of structures.

2. The measurement of in-line and transverse forces alone is no longer sufficient. Extensive research is needed to quantify the effect of spanwise coherence on the in-line and transverse forces and, in turn, on the drag, inertia, and lift coefficients. This will require the measurement of spanwise and chordwise pressure distributions over cylinders.

3. The determination of the effect of lift-induced oscillations on the in-line force is extremely important. The merits of Eq. (69) must be explored through the use of the simultaneous records of the in-line and transverse forces not only for the improvement of the MOJS equation but also for the assessment of the role played by the spanwise coherence of vortices.

4. The contributions of all harmonics of the residue cannot be taken into consideration. From a practical point of view this is rather difficult and certainly not justified in view of the uncertainties associated with the kinematics of the flow field, spanwise coherence of vortices, nonstationary nature of the occurrences, nonuniform surface roughness, and the possible dynamic response of the body to the fluid forces imposed on it. It is because of these reasons that the modified MOJS equation should be restricted to three terms [...Eq. (69)].

5. Flow kinematics under storm driven seas are random and three-dimensional. Experiments must be carried out both in the laboratory and in the ocean environment to simulate all of the important features of storm driven seas at Reynolds numbers larger than 10^6.

6. Basic research should be pursued to determine the role played by the shedding and interaction of vortices in time-dependent flow about noncircular bluff bodies. Such studies will enhance our understanding of the MOJS equation and the limitations of its generalizations.

Appendix F

WBS 2.1.2 WAVE-CURRENT EFFECTS ON
FORCES AND COEFFICIENTS - A FEASIBILITY STUDY*

CONCLUSIONS

The results of this investigation warranted the following conclusions:

1. The speculative generalization of the Morison equation to wave-current loading is not warranted.

2. The drag and inertia coefficients for the harmonic flow alone are not identical with those for the current-harmonic-flow, particularly in the drag-inertia dominated regime. The wake biasing resulting from the current increases the inertia coefficient and decreases the drag coefficient in the said flow regime.

3. The drag and inertia coefficients depend, in general on the Keulegan-Carpenter number, Reynolds number, relative roughness, and the relative current velocity.

4. The force-coefficients obtained from tests at sea (where there are always some currents) are necessarily different from those obtained under no-current conditions. The comparison of the two sets of data is not warranted. The results presented herein show that the drag coefficients resulting from the ocean tests must be smaller than those resulting from the strictly-harmonic-flow experiments with no current. The inverse is true for the inertia coefficient. In view of this conclusion one must seriously examine the validity of the ocean tests in assessing the applicability of the Morison equation to wave loading.

5. The two-term Morison equation (modified for the current) does not adequately represent the measured force even when it is used with the drag and inertia coefficients obtained under appropriate conditions. Larger errors would have resulted from its use had one used the drag and inertia coefficients for the wave or harmonic flow alone.

6. The four-term Morison equation represents the measured force with great accuracy and reduces the residue to almost negligible values.

7. Additional analysis and experiments are urgently needed to cover a larger range of Reynolds numbers and relative current velocities to increase the data base and to put the design of offshore structures on a much more sound basis. The current practice of using the speculative

*Reprint of CONCLUSIONS from Reference 14.

generalization of the Morison equation to the prediction of wave-current loading on offshore structures with the drag and inertia coefficients obtained under questionable conditions is invalid.

8. This investigation, carried out with limited budget -- over a short time period has shown emphatically the importance of the role played by the current and the wake biasing on the calculation of wave forces on offshore structures. Additional experiments will shed considerable light on this important problem and will increase the reliability of the future designs. This, in turn, will result in considerable savings.

Appendix G

WBS 2.2.1 WAVE-CURRENT INTERACTION FLOW FIELD
KINEMATICS FEASIBILITY STUDY

SOME EXPERIMENTS DEALING WITH THE INTERACTION OF CURRENTS AND WAVES*

1. Introduction

The subject of the interaction of waves and currents is one which is of interest in several different types of engineering applications. For example, the problem of forces on marine structures makes it necessary to understand the velocities and accelerations to which a structure is exposed. Indeed, the manner in which a current interacts with a large finite amplitude wave is yet to be fully understood. Another problem deals with the refraction and concomitant attenuation or amplification of waves due to offshore currents. This relates to the change in wave direction and height due to the imposition of a cross-current which may exist for many different reasons. One of these reasons, for example, is the offshore current which is caused by the discharge of large amounts of cooling water by power plants. This induced current can modify the direction and the magnitude of approaching waves and may change the nearshore tranport of sediment associated with these waves.

It was the intent of the study reported herein to provide more experimental information on wave-current interactions. This investigation is an outgrowth of a literature survey entitled "Wave-Current Interactions" by F. Raichlen...(Ref 8). In that study several different approaches to the experimental problem which were avialable in the literature at that time were reviewed with both the advantages and disadvantages of these methods being described. In addition, some theoretical developments were mentioned and briefly described in that report and one of these is applied in this study [by] Thomas [Ref 9]....

A criticism of certain of the experiments conducted in the past is that the method of introducing either the wave or the current into the tank in some experimental programs produced problems of mutual interference. For example, if plunger-type wave machines were used in a steady current, an unsteady current is created due to the periodic blockage of the flow. In general, one problem which is very difficult to eliminate is that the wave as it develops from its generation is exposed to the current and the current may also be developing simultaneously. (This problem is not directly answered by the results of this study.)

One objective of this study was to investigate, using a fairly simple means of introducing and withdrawing a current into the wave tank, the effect of the current inlet on the water particle velocities associated with the wave. The manner by which this current is introduced into the wave tank and the results will be described fully. In addition, the question posed was: Is it possible, for relatively small amplitude waves, simply to use linear superposition or is a numerical method more acceptable? For the possible currents which were available in this study, conclusions could be drawn relative to these two questions.

*Excerpts from Reference 16.

[Figures 9 and 11 are included in this excerpt from Reference 16 as Figures G-1 and G-2.]

5. Conclusions and Recommendations

The following major conclusions and recommendations can be drawn from this study:

1) Even with a relatively simple method of introducing and removing a current from a wave tank, the effects on the wave are relatively small.
2) If distance is available between the measuring position and the current inlet, a reasonably good current velocity profile can be realized.
3) An unknown effect in any current wave system is the effect of the wave on the current and the current on the wave in the region where both of these are developing and before they reach "steady state".
4) For relatively small waves it appears that the linear superposition of the velocities associated with the wave alone and the current alone reasonably predicts the measured total velocity.
5) For the same cases the measured total particle velocity is also reasonably well predicted using the numerical method proposed by Thomas...[Ref 9].
6) To more conclusively define the best numerical theory for predicting wave-current interactions, or if present theories are applicable, it is necessary to conduct experiments with large finite amplitude waves.
7) Because of certain directional considerations and uncertainties with this regard, especially the variability of direction of the resultant velocity with depth for waves and currents crossing at an angle, three-dimensional experiments may be desirable. From the two-dimensional experiments reported herein it can be seen that it may be possible to use a wave basin with the direction of the waves fixed and portable inflow boxes and outflow boxes to change the direction of the current. It also may be possible to use backscattering techniques with laser-Doppler velocimetry to investigate the velocities at a given location.
8) A logarithmic velocity profile resulted in this experiment; however, it may be desirable to modify the velocity profile so that it is more closely related to wind-induced surface currents. Such modifications may be possible using screens extending partially over the depth near the test section. However, with such a modification one must realize that with the imposition of finite amplitude waves, there may not be time (or distance) to fully realize the effect of the current modification on the waves.
9) There appears to be good potential for laboratory experiments in this area and a continued laboratory effort is recommended.

THE INTERACTION OF SOLITARY WAVES WITH CURRENTS*

1. Introduction

An earlier study...[Ref 16] investigated the interaction of periodic waves and currents experimentally. Both favorable and adverse currents were used and velocities were measured using a two-dimensional laser-Doppler velocimeter (LDV). In the experiments the depthwise variation of the horizontal and vertical water particle velocities were obtained: with the current alone, with waves alone, and the combination of waves and current. The objective was to investigate the reliability of the prediction of wave-current interactions from simple linear superposition and from a numerical solution proposed by Thomas...[Ref 9].

A very simple means of introducing the current into the wave tank was used. This consisted of an inlet box and an outlet box each 110 cm wide, 61 cm long, and 13.5 cm high located at each end of a wave tank with the outlet box introducing the flow at one end and the inlet box withdrawing it at the other end. Therefore, the waves propagated over the inlet/outlet box located in front of the wave machine. It was found that the effects of these boxes on the wave were relatively small. Also, for the distance available between the inlet and outlet boxes, the velocity profile near the center of the tank was logarithmic and similar for favorable and adverse currents.

A main conclusion of that earlier study was, for relatively small shallow water waves, the measured total velocity was predicted reasonably well by the simple linear superposition of the velocities associated with waves alone and the current alone. Hence, it was apparent at the conclusion of these experiments that additional studies were needed to investigate more fully the interaction of currents with larger waves, i.e., finite amplitude waves with height-to-depth ratios larger than the value of approximately 0.03 which was tested. Therefore, experiments were planned to investigate the interaction of a current with solitary waves which have a larger relative wave height and these results are reported herein. With larger waves it was important to increase the mean current velocity by a factor of about two compared to that used earlier by Raichlen and Lee...[Ref 16]. This was accomplished by modifying the flow system used to generate the current in that study to incorporate another pump with a larger flow rate. However, due to the larger pump and the necessarily modified piping system, only adverse currents could be generated.

Since the report by Reference 16 fully describes various aspects of the experimental equipment, these will not be discussed in detail here. Certain aspects of the equipment as they relate to these experiments will be described, the experimental conditions will be summarized, and the data which were obtained will be presented and discussed.

[Figure 12 (a through p) from Reference 17 is included in this Appendix as Figure G-3 (a through f)].

*Excerpts from Reference 17.

4. Conclusions and Recommendations

The following major conclusions can be drawn from this study:

1. The wave generation system being used shows excellent reproducibility which is an important aspect of any experiment for point-velocity measurements such as with the LDV.
2. For these experiments, because of the limited water depth over the inlet box, the incident wave is modified significantly by the current producing apparatus.
3. This investigation reinforces the opinion that it is difficult to conceive a method by which both the current and the wave can be introduced into the experimental facility in a relatively undisturbed fashion. What is meant is that a facility can be designed to produce waves alone well and one can be designed to produce currents alone well, but the combination of the two for mechanically produced waves introduces design problems that are not easy to overcome.
4. The current appears to have a greater effect on the shape of the trailing waves in the generated wave group than it does on the shape of the lead solitary wave.
5. The effect of the current on the waves which follow the main leading wave appears to begin at the inlet box.
6. The speed of the leading wave is reduced about 10% by the adverse current, and this result is in good agreement with the simple superposition of the wave speed of the wave along and the current.
7. Comparing the wave profiles with and without the current at Stations 1 and 3, the current appears to shift the wave energy to lower frequencies.
8. A comparison of the time history of the measured horizontal velocities with the time history obtained at the same location by linearly superposing the measured velocity of the wave alone and the current alone indicates reasonably good agreement for the leading wave. Poorer agreement is evident with the trailing waves as would be expected from a comparison of the wave profiles with and without the current.
9. The velocity obtained by linear superposition is generally 10% less than that measured at the crest of the leading wave. The reverse appears true for the trailing waves, but this can be probably attributed to dispersive effects and current effects associated with the trailing waves.
10. The effect of the currents on the veritcal velocities is somewhat more pronounced with regard to higher frequency components. However, the main trends are quite similar.

The following recommendations can be made based upon the results of this investigation:

It is suggested that an expanded program of research be considered to investigate more fully experimentally particular aspects of wave-current interactions. It was not possible in this investigation, due to certain limitation of the experimental equipment, to investigate the effect of large currents on nonlinear waves which are near breaking. (In the experiments reported herein the maximum normalized wave height investigated was 0.3.)

Certain effects have been observed in these experiments particularly in the trailing oscillatory waves following the leading solitary wave which suggest with larger currents and larger waves similar effects would be seen in the leading wave. In addition, studies of wave-current interactions for waves moving at an angle to a current should be initiated.

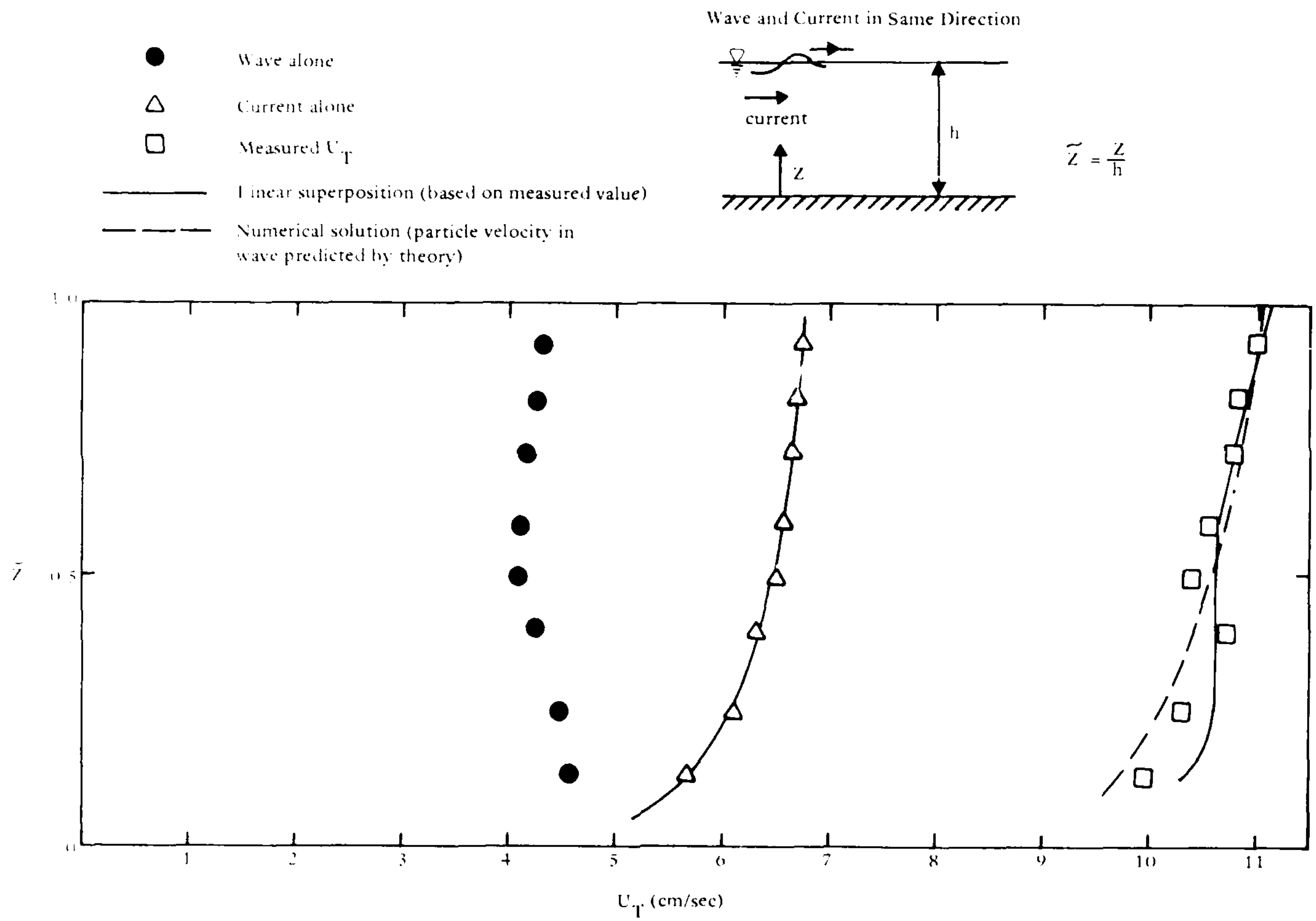


Figure G-1. Depthwise distribution of horizontal water particle velocity for a nearly linear (cnoidal) wave and current propagating in the same direction (favorable current) (Ref 16).

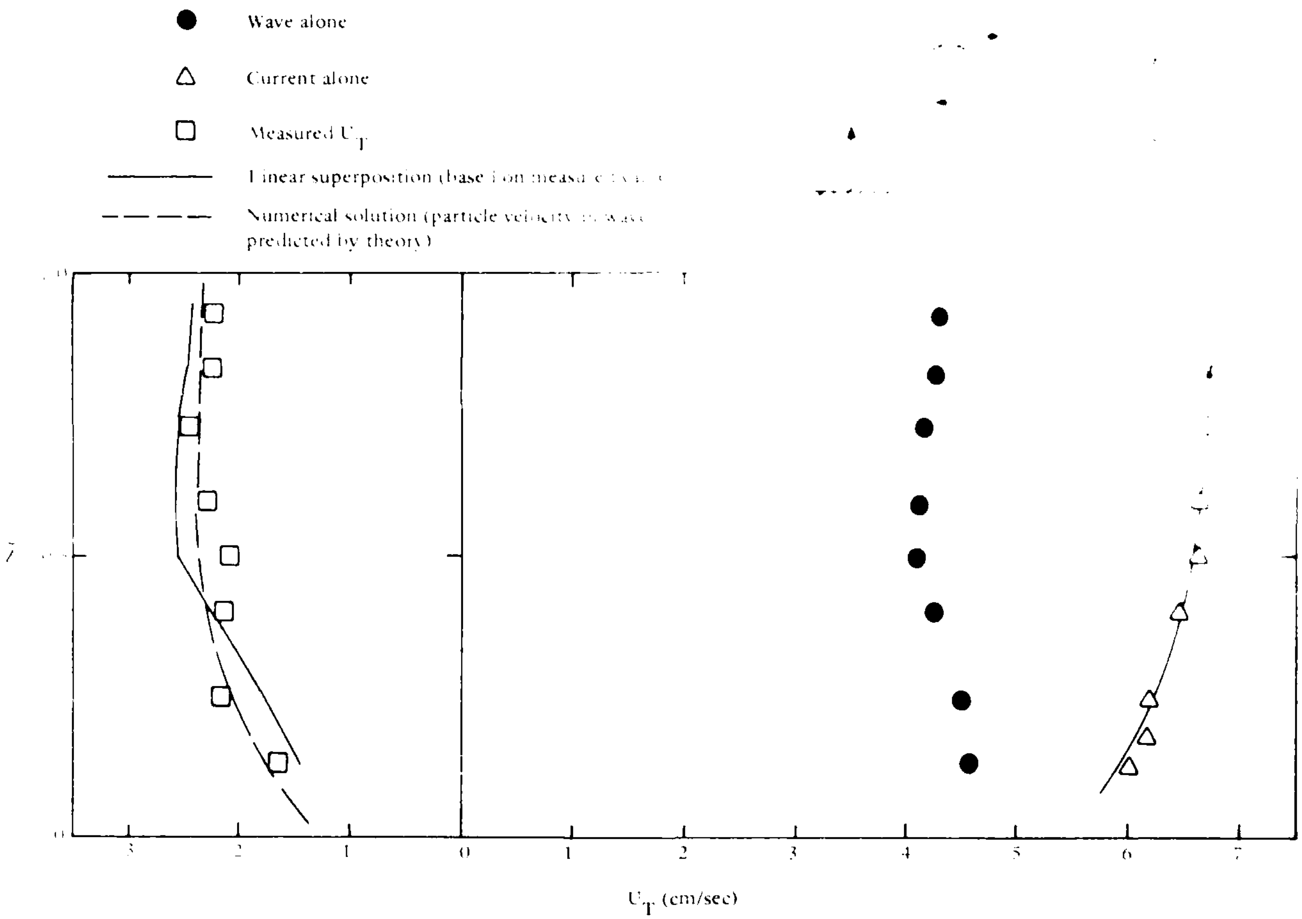
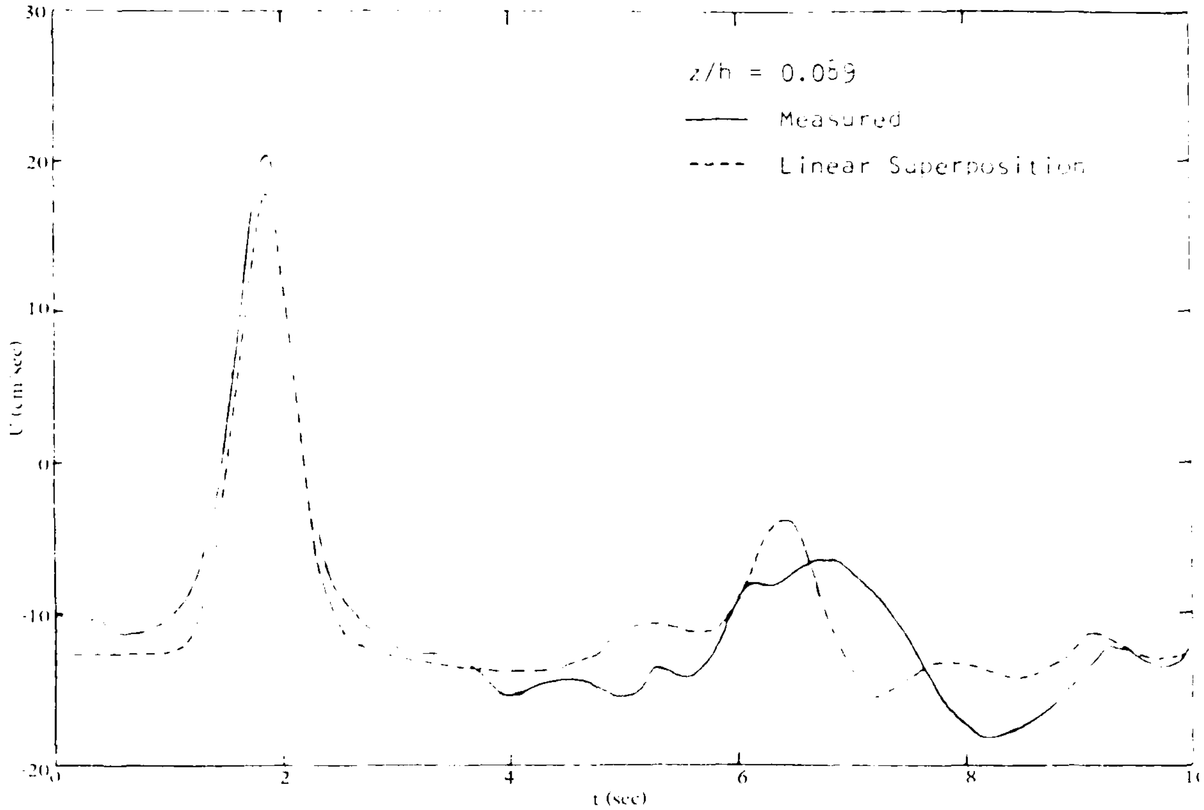
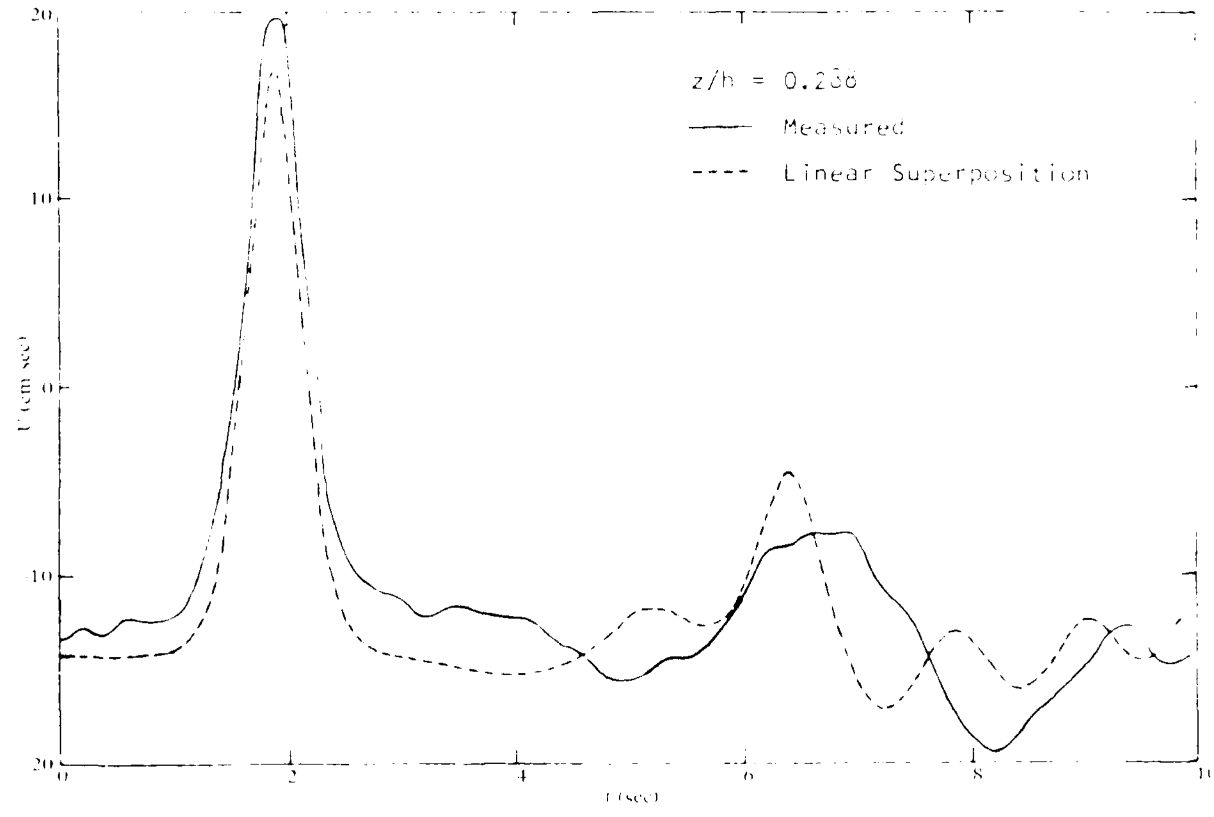


Figure G.2 Depthwise distribution of the horizontal water particle velocity for a nearly linear (cnoidal) wave and current propagating in the opposite direction (adverse current) (Ref 16)

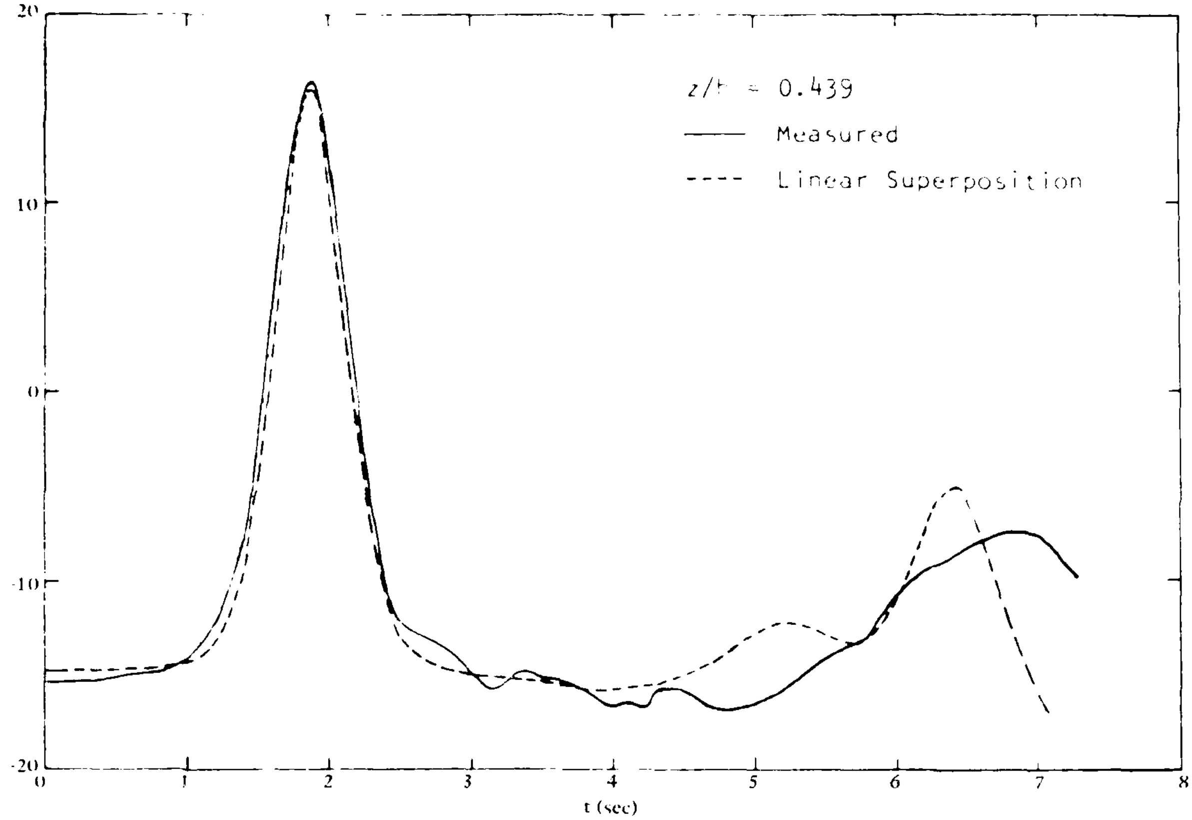


(a) At z/h = 0.089

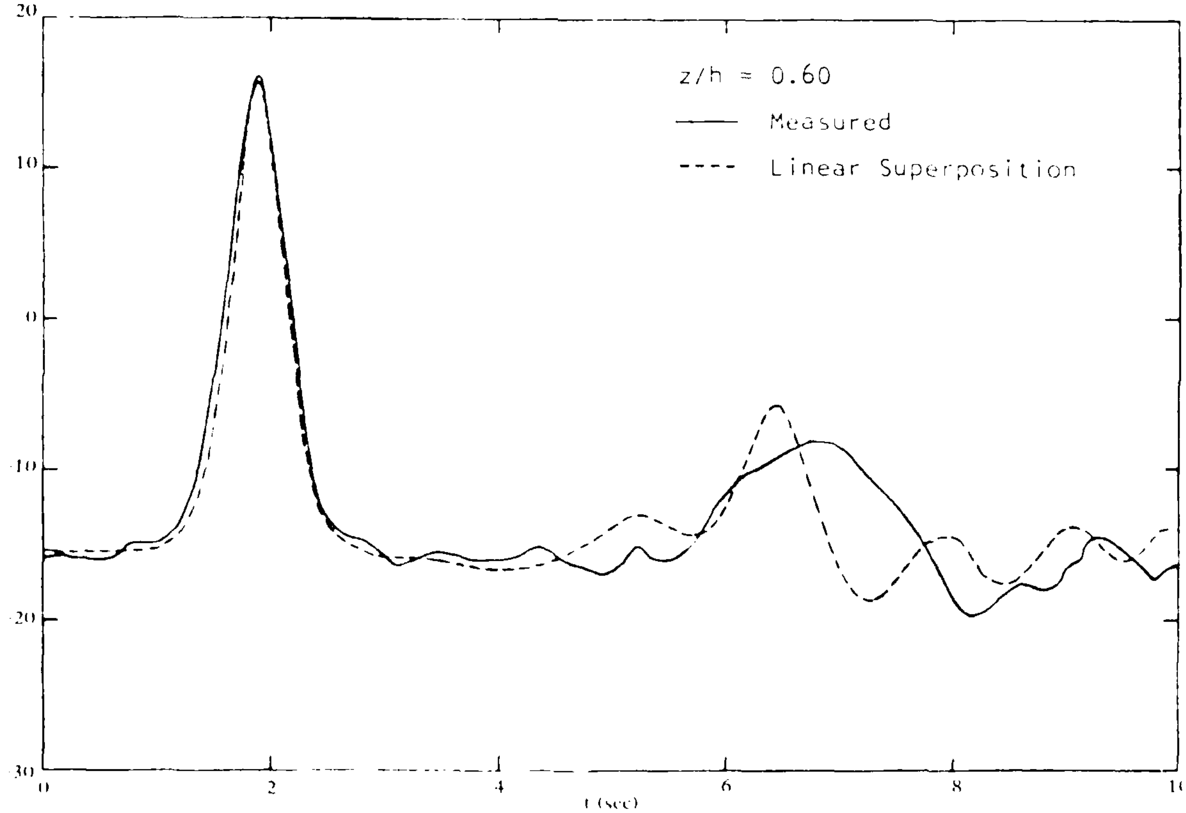


(b) At z/h = 0.288

Figure G-3. Measured versus linear superposition horizontal velocities for a non-linear solitary wave interacting with an adverse current (Ref. 17)

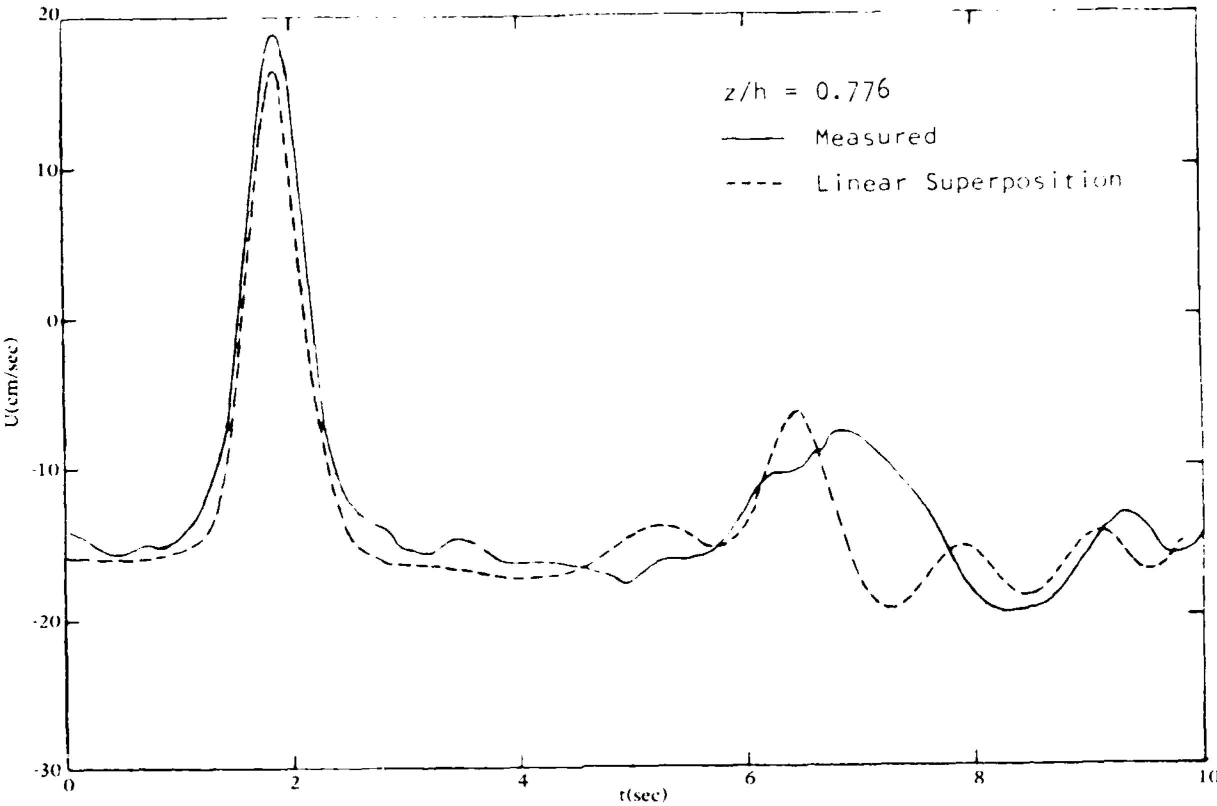


(c) At z/h = 0.43.

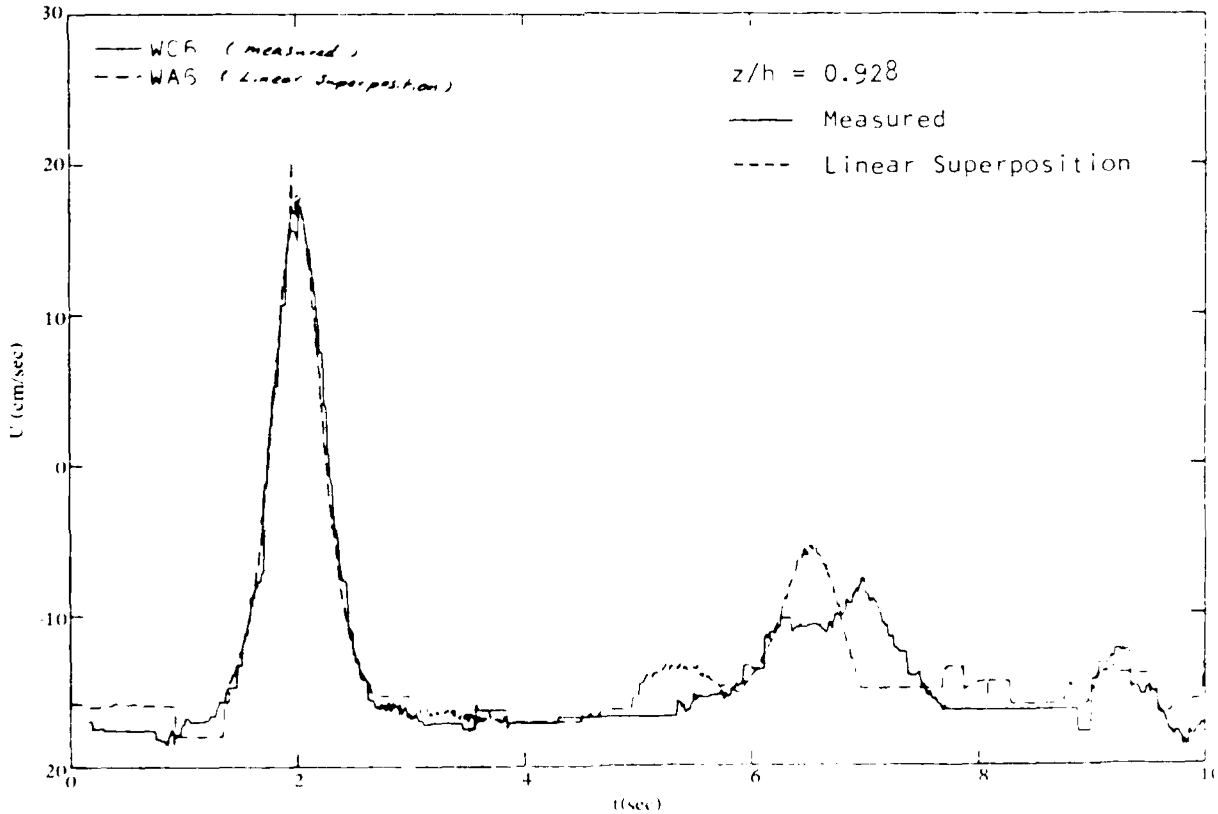


(d) At z/h = 0.60.

Figure G-3. Continued.



(e) At z/h = 0.776.



(f) At z/h = 0.928.

Figure G-3. Continued.

Appendix H

WBS 3.1 MORISON EQUATION FORCE COEFFICIENT SELECTION AND PARAMETERIZATION

Problem: Guidelines must be provided for determining the parametric dependency of the Morison equation force coefficients; for distinguishing coefficients computed using field data from coefficients computed using laboratory data; for evaluating the condition of either field or laboratory data for computing force coefficients; for evaluating the various numerical methods employed to compute force coefficients; for selecting the appropriate coefficients to use with various wave theories on either vertical, horizontal, or inclined members; and to identify the effects of kinematics choice, ambient current fields, and marine growth roughness.

The level 3 tasks identified in Figure 11 have been described (Tables H-1 through H-7) and scheduled below (Table H-8). Each task will be addressed by an expert in the field. New research will not be undertaken but rather a summary made of current state-of-the-art knowledge and then its comparison with current standard operating procedures. A structured format with tabular summaries will be established before any tasks are initiated and all the experts will provide their results in this unified structured summary. These results can then be included easily in existing NAVFAC documents. The sequence of the task scheduling is important to optimize the exchange of information among the noted experts chosen to complete each individual task. Thus, editorial comments by the team of experts can be made on the various individual tasks.

Approach: The parametric dependency and selection criteria for the drag and inertia coefficients used in the Morison equation require definitive guidelines for each of the level 3 tasks identified in Figure 11. Each task identifies specific topics relevant to the selection of the drag and inertia coefficients for engineering design applications. Tabular summaries of relevant past experimental efforts for each topic will be provided for each task. A chronological summary of these same experimental efforts will be provided in Task 1.

Task 1: Dimensional Analyses and Parameters. The cognizant expert shall provide definitive guidelines for determining the parametric dependency of the Morison equation force coefficients. Since the dimensionless parameters obtained depend on the selection of the independent and the repeating variables, several alternatives for choosing these variables must be presented. Preference shall be given to the Hunsaker and Rightmire method for illustrating these alternatives because this method emphasizes the physical relevance to engineering applications of the repeating variables. Included in the alternative selection of independent variables must be guidelines for determining the implication of selecting primitive variables compared to nonprimitive variables (e.g., μ, ρ versus ν; or H, T, g versus U_{max}; or T versus ω where μ = dynamic viscosity, ρ = fluid density, ν = kinematic viscosity, T = wave period,

g = gravitational acceleration, U_{max} = maximum horizontal orbital component of velocity and ω = angular frequency). Tabular summaries of the relevant past studies and reported coefficients shall be provided (see Ref 7). Table H-1 represents a possible type of tabular summary that would be expected to be incorporated in these guidelines.

Task 2: Laboratory and Field Data. Laboratory data have been reported on either oscillating water columns (U-tubes), oscillating cylinders in still water, or free surface waves. In addition, the free surface laboratory wave studies have either been progressive or standing wave tests. The standing wave tests on cylinders have been conducted on horizontal cylinders placed beneath the node of the standing wave and, therefore, are approximately equivalent to the U-tube horizontal harmonic flows. The experts shall provide definitive guidelines for distinguishing between laboratory data collected in oscillating flows past fixed cylinders and that collected in oscillating cylinders in otherwise still water. The free surface effects and radiated wave energy must also be accounted for in the oscillating cylinder cases. This task should be sequenced to follow the previous parametric dependency task. The results should be included in a tabular summary similar to Table H-2. The summary must reference the topics relevant to the selection of the drag and inertia coefficients.

Either unusually detrimental or significant features of each data set must be as specifically identified as possible. This is especially important for field data in which the free surface effects, methods of data recording and reduction, methods of regression analyses, knowledge of ambient currents, measured kinematics, and the design of the force dynamometers may significantly affect or contaminate the data. The expert must also emphasize the relevance of these data to engineering design applications. This task should follow Task 1 and may be concurrent with Tasks 3 and 4.

Task 3: Correlation With Measured Versus Theoretical Kinematics. The expert shall provide definitive guidelines for evaluating, and for distinguishing between, the effects of using either measured or theoretical kinematics in solving for the force coefficients. These effects shall be summarized relative to the application of the coefficients to engineering design.

For field data, special attention must be given to the effects of spatial separation between the force dynamometer and the velocity meters. The determination of both local and convective accelerations must also be addressed. If theoretical kinematics are employed, the effects of symmetric versus asymmetric wave theories and local versus total accelerations must be provided in the guidelines.

For laboratory data, the measured kinematics for free surface progressive wave data must be carefully reviewed for the effects of spatial separation, boundary interference, ambient noise, and wave basin circulations.

For both field and laboratory data, the guidelines should specifically address calibration, repeatability, and numerical methods used in the regression analyses. Tabular summaries shall be provided similar to Table H-3 which is referenced to relevant topics. The narrative material

should be sequenced and prepared by topic rather than chronologically by experiment. Emphasis will be placed on the relevance of the kinematics relative to coefficient selection for engineering design application. This task should follow Task 1 and may be concurrent with both Tasks 2 and 4.

Task 4: Effects of Artificial and Marine Roughness. The expert shall provide definitive guidelines for distinguishing between artificially roughened cylinders (usually uniformly graded sand or gravel particles) and marine- or macro-roughened cylinders (usually substantially larger roughness elements which are decidedly nonuniform in their distribution). Recent laboratory experiments have been conducted on artificially marine-roughened cylinders having both rigid and flexible roughness elements. Marine-roughened data must also be examined to determine the increase in effective member diameter. The relationship between roughness and the critical Reynolds number in steady flow must be extended to include the data from oscillatory flow studies. The hydrodynamic effects on roughened cylinders in oscillatory flows are further complicated by wake effects and must be fully addressed. The expert will provide a tabular summary similar to Table H-4. The narrative material, sequenced by relevant topics rather than by chronological experiments must emphasize the relevance of the data to engineering design applications. This task should follow Task 1 and may be concurrent with Tasks 2 and 3.

Task 5: Lift Effects on In-line Forces. The noted expert will provide definitive guidelines on the effects of lift and transverse forces and moments on the Morison equation force coefficients. The effects of wake biasing and spanwise coherence are known to have a substantial influence not only on the lift coefficients but on the drag and inertia coefficients for the in-line forces and moments as well. The lack of repeatability and the apparently stochastic nature of transverse forces in purely sinusoidal flows has been documented and must be addressed. The correlation of nonrepeatable lift forces into spectral harmonics and the correlation of repeatable lift forces with fundamental frequencies must be addressed and related to engineering design applications. The expert will provide tabular summaries similar to Table H-5, and the narrative should be sequenced by relevant topic rather than chronologically by experiment. Emphasis should be placed on relevance of the transverse lift forces to engineering design applications. This task should follow Tasks 1 to 4 and may be concurrent with Tasks 6 and 7.

Task 6: Effect of Member Orientation. The expert will provide definitive guidelines for assessing the effects of member orientation on the drag and inertia coefficients. The generalizations of the Morison equation to horizontal and inclined members from its original application to a vertical pile have also resulted in modifications to the kinematic fields. Those modifications will influence any regression analyses used to compute drag, inertia, or lift coefficients. The expert will provide tabular summaries similar to those in Table H-6. The narrative, sequenced by relevant topic rather than chronologically by experiment, will emphasize the relevance of the effect of member orientation on engineering design applications. This task should follow Tasks 1 to 4 and may be concurrent with Tasks 5 and 7.

<u>Task 7: Currents</u>: The expert will provide definitive guidelines for assessing the effects of current on the drag, lift, and inertia coefficients. Of particular importance is the measurement of the current, the incidence angle relative to the direction of wave propagation, the type of regression analyses, the spanwise coherence of the vortex shedding, and generalization of the Morison equation used in the regression analyses. Guidelines regarding the appropriateness of linear superposition, the inclusion of wave-current interaction, the theories in the regression analysis coefficient solutions, and the steadiness and uniformity of the experimental current profiles are to be specifically included. Special attention shall also be given to laboratory experiments in order to ascertain the error introduced by collecting data during the transient interaction period before steady state conditions are achieved (e.g., cylinders translated from rest in waves or oscillatory flow). The expert will provide tabular summaries similar to Table H-7. The guideline narrative will be sequenced by relevant topic rather than chronologically by experiment. The expert will also emphasize the relevance of the effects of current on engineering design applications. This task should follow Tasks 1 to 4 and may be concurrent with Tasks 5 and 6.

Table H-1. Example of Possible Tabular Summary of Force Coefficients Studies

Reference	Chronological
Test Type	Field; laboratory; both
Sea State	Periodic; random; osc. cyl
Analyses	Least sqs; FFT; both
Kinematics	Measured; theoretical
Currents	None; not measured; measured (incidence angles)
Cylinder Orientation	Vertical; horizontal; inclined
Variables	H, T, d, μ, U_{max}, D, ρ, ε, g
Parameters	K, Re; β, a/D; ε
Range	x < K < xx; Re < 10y; β < xyz
Errors	RMS; max; none
Results	C_d, C_m, C_l vs Re; C_d, C_m, C_l vs β; C_d, C_m, C_l vs K

Table H-2. Example of Possible Tabular Summary by Test Type and Relevant Topics

Test Type	Laboratory first; field second
Kinematics	Measured first; theoretical second
Sea State	Periodic; random; osc. cyl.
Analyses	Least squares; Fourier
Currents	None; not measured; measured (incidence angles)
Cylinder Orientation	Vertical; horizontal; inclined
Parameter Range	Depends on parametric dependency task
References	Chronological
Results	Design relevance; potential error magnitudes

Table H-3. Example of Possible Tabular Summary by Kinematics and Relevant Topics

Kinematics	Measured first; theoretical second
Test	Laboratory first; field second
Currents	None; not measured; measured (angle of incidence)
Sea State	Periodic; random; osc. cyl.
Analyses	Least sqs; FFT; both
Cylinder Orientation	Vertical; horizontal; inclined
Parameter Range	Depends on parametric dependency task
References	Chronological
Results	Design relevance; potential error magnitudes

Table H-4. Example of Possible Tabular Summary by Roughness and Relevant Topics

Roughness	Artificial first; marine second
Test	Laboratory first; field second
Sea State	Periodic; random; osc. cyl.
Kinematics	Measured; theoretical
Analyses	Least sqs; FFT; both
Cylinder Orientation	Vertical; horizontal; inclined
Parameter Range	Depends on parametric dependency task
References	Chronological
Results	Design relevance; potential error magnitudes

AD-A141 952 TECHNOLOGY DEVELOPMENT PLAN FOR DESIGN GUIDELINES FWR WAVE-INDUCED HYDROD..(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA J M DUMMER ET AL. MAR 84 NCEL-TN-1690 2/2

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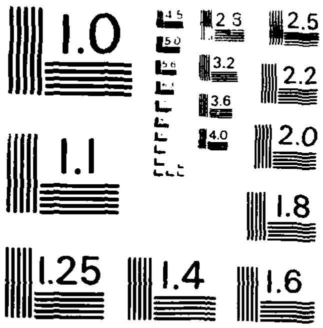

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Table H-5. Example of Possible Tabular Summary Of Lift Effects and Relevant Topics

Test	Laboratory first; field second
Kinematics	Measured first; theoretical second
Sea State	Periodic; random; osc. cyl.
Analyses	Least sqs; FFT; both
Currents	None; not measured; measured (incidence angle)
Cylinder Orientation	Horizontal; vertical; inclined
Parameter Range	Depends on parametric dependency task
References	Chronological
Results	Design relevance; potential error magnitudes

Table H-6. Example of Possible Tabular Summary
Member Orientation and Relevant Topics

Orientation	Vertical first; horizontal second; inclined last
Test	Laboratory first; field second
Sea State	Periodic; random; osc. cyl.
Kinematics	Measured; theoretical
Analyses	Least sqs.; FFT; both
References	Chronological

Table H-7. Example of Possible Tabular Summary of Effects of Currents and Relevant Topics

Current	Sequence by topic
Test	Laboratory first; field second
Sea State	Periodic; random; osc. cyl.
Kinematics	Measured; theoretical
Analyses	Least sqs.; FFT; both
Incident Angle	Oblique; perpendicular; co-linear
Orientation	Vertical; horizontal; inclined
Parameter Range	Depends on parametric dependency task
References	Chronological
Results	Design relevance; potential error magnitudes

Table H-8. Time Schedule: Force Coefficient Selection and Choice of Parameter Topics

Task	FY84				Remarks
	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	
1. Dimensional Analysis, Parameters, Experimental Review					
2. Laboratory vs. Field Data					
3. Measured vs. Theoretical Kinemetics					
4. Artifical and Marine Roughness Effects					
5. Lift Effects – In-Line and Transverse					
6. Member Orientation Effects					Combine with 2, 4, and 5
7. Current Effects					Combine with 3
8. Edit and Review Process					

Appendix I

MORISON EQUATION DETERMINISTIC STATIC ANALYSIS

Problem: Existing guidelines in NAVFAC DM 26 series need to be updated to reflect the SOA and the SOP employed by the offshore petroleum industry. Since the technologies required to update the NAVFAC DM 26 series are largely held proprietary by the offshore petroleum industry, these technologies must be acquired from alternative sources. These technologies, however, must become organic to the NAVFAC SOA and SOP to achieve safe and economical designs. Definitive guidelines are required for small members whose hydrodynamic loadings must be computed using the Morison equation and the Froude-Krylov hypothesis. Definitive guidelines are required to select the most appropriate drag, inertia, and lift force coefficients and the most applicable wave theory for the wave force design regime. In addition, definitive guidelines must be provided for including current loadings, inclined members, wave slamming, transverse lift force loadings, interference effects between closely spaced members, and corrections for the free surface effects which must be applied to the Morison equation in order to obtain atmospheric pressure at the free surface.

The level 3 tasks identified in Figure 11 are described in Tables I-1 through I-7 and sequenced in Table I-8. Establishment of a structured format with tabular/graphical summaries prior to the initiation of any of these tasks is recommended in order to facilitate the incorporation of these guidelines in the NAVFAC DM 26 series. The sequence of the task scheduling must be observed in order to optimize the exchange of information between the noted experts chosen to complete each individual task. Thus, expert editorial comments can be made on the various individual tasks from the expert team.

Although the tasks described in this appendix are referenced to the Morison equation deterministic, static wave force analysis, all are applicable and pertinent to the random, dynamic wave force analysis as well. For brevity, these descriptions are not repeated in the random, dynamic, wave force analysis (Appendix J).

Approach: Each of the level 3 tasks of the Morison equation deterministic static analysis identified in Figure 11 require definitive guidelines in order to reflect the SOA and the SOP employed by the offshore petroleum industry using largely proprietary design procedures. Tabular/graphical summaries for each of these tasks will be provided and carefully cross-referenced to the specific topics and reported experimental results for that task. A chronological summary of all of the relevant experimental results will be provided in Task 1.

Task 1: Selection of Appropriate Coefficients and Wave Theory. An expert will establish definitive guidelines for the selection of appropriate drag, inertia, and lift force coefficients for the wave current model and wave theory selected to represent the kinematic field. The guidelines

shall be limited to the deterministic static applications of small cylinders in the Morison equation wave force regime. Since methods of analyses of both field and laboratory data as well as the parametric dependency of the Morison equation force coefficients have been reviewed in detail (see Appendix H), the emphasis here will be placed on the relationship between these force coefficients and the wave theory/current model used to represent the kinematics. Special attention shall be given to the selection of force coefficients appropriate for the following wave theory kinematics: linear, nonlinear (e.g., stream function or Stoke's fifth-order theories), shallow sinusoidal, and Cokelet steep symmetric. Of special importance shall be definitive guidelines directed toward the selection of appropriate force coefficients to use with the stream function graphs for total force and total moment which are included in DM 26.2 (see Figures 135 to 138, and Figures 139 to 142, of Ref 2). Attention will also be given to the selection of force coefficients for both translational and rotational relative motion conditions.

Also included in these guidelines shall be the kinematics field on inclined small members and the effect of this orientation on both the kinematics and force coefficients.

An appropriate structured format will be established by this task which may be used to integrate and to cross-reference the subsequent tasks. Table I-1 provides an example of a possible summary of the guidelines provided by this task. The narrative in the guidelines shall be sequenced in relation (and referenced) to the final tabular summary selected.

In order to avoid duplication of effort, this task must be initiated subsequent to the previously described tasks (see Appendix H) accomplished under the "Force Coefficient Selection and Parameters" level 2 task shown in Figure 12.

Task 2: Wave-Current Loading. The expert will provide definitive guidelines to establish the appropriateness of the various forms of the Morison equation for modeling deterministic wave forces when a current is present. Attention will be given to the selection of the appropriate force model, force coefficients, and kinematics theory. The kinematics theory will be required to yield accurate velocities and accelerations for co-linear and multiple heading wave-current incidence angles on small body structural members. Appropriate wave-current regimes for the use of simplistic analytical kinematics approximations, such as linear superposition, and the expected kinematics and attendant force errors will be identified. Complexity, accuracy, and computational expense will be addressed for numerical wave-current kinematics models. The effect of a "stopping current" on design applications will also be included. The expert should provide a narrative summary similar to Table I-2 with emphasis on wave-current interaction relevance to the appropriate selection of the Morison-type force model, force coefficients, and kinematics model. This task should be accomplished subsequent to Task 1 and concurrently with Tasks 3, 4 and 5.

Task 3: Inclined Members. The expert will provide definitive guidelines on selection of the appropriate Morison equation force model applicable for inclined and horizontal structural members. Four different Morison models have been identified in Reference 22 for inclined member

applications. Descriptions of these and any other existing models and their ranges of accuracy and applicability will be provided. Specifically addressed will be the evaluation of the appropriate instantaneous velocities, accelerations, and angle of incidence relative to the inclined member. The significance of the methods used to establish the projected cross-sectional area for the drag term and the displaced volume for the inertial term will be identified. Attempts will be made to describe the physics of the fluid flow and the variation in flow separation and wake formation as the instantaneous velocity and acceleration vectors rotate about the members. This description will be provided in both pictorial and narrative formats. The vertical, horizontal and inclined member cases will be compared with each other and with descriptions indicating how the inclined cases tend asymptotically toward either the vertical case or horizontal case with member rotation in the vertical or horizontal planes, respectively. Existing experimental data will be evaluated and comparisons made of the theoretical and measured forces for deterministic wave cases.

The expert will provide a tabular summary similar to Table I-3 with emphasis on the design relevance of inclined members and the attendant force modeling techniques. This task should be accomplished subsequent to Task 1 and concurrently with Tasks 2, 4, and 5.

Task 4: Wave Slamming. The expert will provide definitive guidelines for selecting the appropriate wave slamming coefficient to use for small members which may be treated by static equivalent methods (i.e., the relative motion response of the member may be neglected). Special attention shall be given to the usually invoked assumptions regarding fluid viscosity, irrotational flow, air cushioning, air boundary layer, and residual free surface turbulence, as well as to the horizontal, vertical, or inclined orientation of the member. Transient effects must also be addressed. Since the emphasis here will be on a "static equivalent" design, a careful distinction must be given to the selection of wave slamming coefficients for analyses which will not include the dynamic response of the member. The expert will provide tabular summaries similar to Table I-4 Narrative material shall be sequenced and cross-referenced to the tabular summaries for easy application to design. This task should follow Task 1 and may be concurrent with Tasks 2, 3, and 5.

Task 5: Transverse Forces. The expert will establish definitive guidelines for determining the transverse lift forces on small members designed by the static equivalent method. These effects must be documented for vertical, horizontal or inclined members. The increase in the in-line resultant force due to transverse lift forces must be accounted for in design by either a modification of the force coefficients in the Morison equation or by the addition of another force term. Design recommendations for the most appropriate method for a static-equivalent design is required. Of special concern is the lack of repeatability for transverse forces which oscillate at twice the fundamental wave period compared to the relatively more repeatable transverse force which oscillates at the fundamental wave period. The determination of the most appropriate model for linear and nonlinear waves both with and without current is required. Tabular summaries similar to Table I-5 are required. The

narrative must be sequenced and cross-referenced to the tabular summary. This task should follow Task 1 and may be concurrent with Tasks 2, 3 and 4.

Task 6: Interference Effects. The expert will provide definitive guidelines for determining mutual interference between adjacent and contiguous members. The attendant effects on the force model predictions as well as the choice of drag, lift, and inertial coefficients and theoretical kinematics required by the force model will be described. The kinematics effects will address both linear and nonlinear theories either with or without a current. Evaluation of interference effects as a function of orientation and separation distance via relative wave amplitude and wave length parameters will be given special attention. Equivalent transformations for representing an array of members subject to interference by an equivalent single member must be addressed. Tabular summaries similar to Table I-6 will be provided. The narrative will be cross-referenced to the tabular summary. This task should follow Tasks 2, 3, 4, and 5 and may be concurrent with Task 7.

Task 7: Free Surface Effects. The noted expert will provide definitive guidelines for computing wave force loadings on small members near the free surface. Free surface effects on horizontal, vertical, and inclined members, both with and without currents, using both linear and nonlinear wave theories will be described. Special attention shall be given to providing design recommendations for reducing the drag, inertia, and lift force coefficients within two dimensionless velocity heads of the instantaneous free surface. These free surface corrections are required in order to reduce the pressure force to zero (i.e., atmospheric pressure conditions) at the free surface using the Morison equation force model. These guidelines should be applicable within two dimensionless velocity heads below the instantaneous free surface for all members which are unaffected by wave slamming forces.

This task should follow Tasks 1, 2, 3, 4 and 5 and may be concurrent with Task 6. The guidelines should be provided in a tabular summary similar to Table I-7 and the narrative description should be sequenced and referenced to the tabular summary.

Table I-1. Example of Possible Summary for Selection of Coefficients and Wave Theory

Wave Theory	Parameters	Orientation	Recommended Values		References
			Without Current	With Current	
Linear	Reynolds No.	Vertical	C_d C_m C_l	C_d C_m C_l	
Stream Function	Keulegan-Carpenter No.	Horizontal		Incidence Angle	
Stokes II III, V		Inclined			

Table I-2. Example of Possible Wave-Current Interaction Effects Table

Incidence Angle	Variations	Errors	Theories	Recommendations	References
Following	Horizontal		Linear		Chronological
Adverse	Vertical		Nonlinear		
Oblique	Temporal		Numerical		

Table I-3. Example of a Possible Inclination Effects Summary

Force Model	Inclination	X-Area	Displaced Volume	Coefficient Effect	Current	Kinematics	Application and Results	Data Source	Reference
	Vertical plane	Rectangular	Inclined		With	Incidence angle, normal components, measured, theoretical	Errors, design relevance	Lab	Chronological or by inclination
	Horizontal	Ellipse	Cylindrical		Without			Field	case
	Both								

Table I-4. Example of Possible Wave Slamming Effects for "Static Equivalent" Design

Orientation	Assumptions	Parameters	Coefficient Values	References
Vertical	Boundary layer	Keulegan-Carpenter		Chronological by topic
Horizontal	Spray	Reynolds No.		
Inclined	Viscosity	Relative amplitude		

Table I-5. Example of Possible Transverse Force Summary

Orientation	Theory	Period	Parameter	Currents	Recommendation	References
Vertical, Horizontal	Linear	Fundamental	Keulegan-Carpenter	With (incidence angle)		Chronological by topic
Inclined	Nonlinear	Second harmonic	Reynolds No.	Without		

Table I-6. Example of a Possible Interference Effects Summary

Force Model	Wave Theory	Current	Orientation	Separation Parameters	No. of Members	Coefficients	Application and Results	Data Source	Reference
	Linear	With (incidence angle)	Vertical	$\frac{S}{H/2}$	Single	C_D, C_L, C_M	Errors, Design Relevance	Lab	Chronological order by topic
	Nonlinear	Without	Horizontal	S/L	Multiple (bents)			Field	

Table I-7. Example of Possible Free Surface Effects Summary

Orientation	Criterion	Parameters	Wave Theory	Current	Recommendations	References
Vertical	2 vel. hds	Keugelan-Carpenter	Linear	With (incidence angle)		Chronological by topic
Horizontal	Others	Reynolds No.	Nonlinear	Without		
Inclined		Other				

Table I-8. Time Schedule

Morison Equation Deterministic Static Analysis Topics

Task	FY84		FY85		Remarks
	3rd Qtr	4th Qtr	1st Qtr	2nd Qtr	
1. Coefficient-Kinematic Theory Selection vs. Force Model					
2. Wave-Current Loading					
3. Inclined Member Force Models					Combine with #1
4. Wave Slamming Models					
5. Transverse Force Models (+In-Line Effects)					
6. Mutual Interference Effects					
7. Free Surface Effects					
8. Edit and Review Process					

Appendix J

WBS 3.3 MORISON EQUATION RANDOM DYNAMIC ANALYSIS

Problem: Existing guidelines in the NAVFAC DM 26 series are restricted to the deterministic static equivalent analyses of rigid offshore structures sited in relatively shallow water. Deep water, small-diameter member structures are typically more compliant; hence, a deterministic static analysis may not be appropriate. The NAVFAC DM 26 series needs to be updated and augmented to reflect the dynamic response of small member structures to nonperiodic wave forces. The analytical and numerical structural algorithms needed to compute the dynamic response of compliant structures are relatively well-established provided the appropriate hydrodynamic fluid loading forcing function is known. Since the fluid loading is coupled to the mass and damping matrices for relative motion structures, the technologies required to accurately prescribe the hydrodynamic loadings must be developed. While the technologies required to describe the hydrodynamic loadings for deterministic static small member structures are relatively well-known (albeit proprietary to the offshore petroleum industry), the technology base required to describe the hydrodynamic force loadings on small member compliant structures is essentially nonexistent (primitively developed, at best) even for the offshore petroleum industry. In order to provide definitive guidelines for the hydrodynamic force loadings for relative motion small members, it is necessary to develop the level 3 technologies identified in Figure 11 for "Random Dynamic Analysis." Several of the level 3 tasks previously described (see Appendix I) for the "Deterministic Static Analysis" case are also pertinent to the random dynamic topic but are not repeated here (for the sake of brevity) unless a discrepancy exists between the two technologies. Table J-1 presents the time schedule.

Approach: Each of the Morison equation random dynamic analysis tasks identified in Figure 11 require definitive guidelines in order to establish the current state-of-the-art technology levels. Industry and government have financed research pertinent to these tasks which is documented and available in the public domain. This research needs to be summarized and incorporated, where appropriate, into a series of NAVFAC design guidelines for future inclusion in Navy design manuals. Tabular or graphical summaries will be compiled for each of these tasks by noted experts in each particular field. A chronological or topical summary of all of the relevant available experimental results will be provided for each of the tasks.

Task 1: Probability and Statistics: Antisymmetric Wave Force Probability Distribution. Dynamic analyses of compliant platforms require probabilistic models to reflect the random nature of real ocean waves. Statistical measures of the ocean surface, such as the significant wave height and period, are required to describe the random nature of these areas. An accurate description of the joint probability density function for wave heights and periods is especially critical since these

two parameters (viz., wave height and wave period) are totally uncorrelated by deterministic linear wave theory. Careful attention must be given to the distinctions as well as the similarities between probability models and statistical models. Of special concern is the obvious paradox that real ocean waves demonstrate a marked asymmetry above the still-water level. This is evident in their measured cumulative distributions due to the sharper, shorter crests and longer, flatter troughs as a consequence of nonlinear wave-wave interactions. In contrast, the Gram-Charlier or Edgeworth Type II analytical probability distribution model derived from the nonlinear boundary value problem is a symmetric probability distribution. Only the heuristic Gaussian-to-Gamma transformation reflects this asymmetry. In addition to the probability models for the sea surface realization, the nonlinear effects on the probability distributions of the envelope or amplitudes must also be addressed. The five-parameter generalized Gamma distribution has been suggested as one possible model for describing the non-Rayleigh behavior of the distribution of amplitudes. Verifications of the generalized Gamma distribution have been severely biased by the methods of determining amplitude; viz., zero up-crossing or zero down-crossing which effaces the positive minimum and the negative maximum from the measured realizations. The probabilistic models for the non-Gaussian and the non-Rayleigh nature of ocean waves and wave forces deserves special attention.

Spectral representations of ocean waves are required for frequency domain analyses of wave forces and must be described in detail. Both the two-parameter and generalized five-parameter spectra must be reviewed with regard to estimating these parameters for design. Time domain analyses which retain strong nonlinearities must also be evaluted. Both the Cartwright and Longuett-Higgins and the Vanmarcke spectral bandwidth parameters for evaluating narrow-banded processes deserve careful attention for engineering design applications.

Both long-term and short-term statistics are required for engineering design. The use of both wind data and wave data in estimating design parameters must be described as these two complementary methods are widely used in the offshore petroleum industry.

A definitive guideline is required to document the SOA of the above-described technology. This guideline will also include a tabular summary of existing research results presented either in chronological or topical order. The narrative will be cross-referenced to the tabular summary and will identify the significant experimental results. Task 1 should be accomplished concurrently with Tasks 2 to 4 and prior to Tasks 5 to 9.

Task 2: Directional Spectra. For physical processes having spectral representation, the frequency domain spectral moments may be related to the statistical properties required in order to completely represent the probability distribution in the time domain. Alternatives to the two- and five-parameter frequency spectra are the directional, spatial spectra. Guidelines are required for evaluating the various directional spreading functions used for engineering design; especially the $\cos^{2n}(\theta - \theta_o)$ and the more computationally efficient wrapped normal functions. Of special concern is the applicability of the assumption of linear independence between the direction angle, θ, and frequency, f. The effects of including

directional spreading functions on the computation of random wave forces on small member space frame structures have been shown to be significant. Applications of these spreading functions to compute wave force loadings by the Morison equation in both the time and frequency domains must be addressed and definitive guidelines established.

These guidelines will document the current SOA for directional-spectra technology. Pertinent research results will be identified in a tabular summary format. The expert will cross-reference the narrative report to the tabular summary of previous research. Design relevance and applicability of directional-spectra technology as well as potential error magnitudes will be specifically identified. Task 2 may be conducted concurrently with Tasks 1, 3, and 4 and prior to Tasks 5 to 9.

Task 3: Extreme Value Statistics. Estimation of extreme values with regard to wave force loadings requires extrapolating beyond the presently available statistical data base. Since the time scale is greatly expanded for the extreme value data, the usual assumption of a continuously stationary process is no longer valid. The analytical or theoretical distributons currently available must be reviewed and guidelines provided with regard to their applications to both real ocean waves and random wave forces on small member structures computed by the Morison equation. Also included must be design guidelines for discontinuous processes such as the intermittent submersion of members above the still-water level. Such discontinuous processes may be described by a Poisson probability distribution. Attention will also be given to extreme value distributions such as the exponential; log-normal; Extremal Type I, II, and III; Weibul; and Gumbel distributions.

The definitive design guideline will document the above SOA technology. This guideline will provide a tabular summary where significant research results are identified. The narrative descriptions will reference the tabular summary, and the design relevance and application of this technology will be specifically identified. Task 3 may be conducted concurrently with Tasks 1, 2, and 4 and prior to Tasks 5 to 9.

Task 4: Revised Case D Stream Function Table. Dynamic analyses by time domain methods are frequently employed in order to retain the nonlinearities. The Corps of Engineer Stream Function Tables (Ref 18) have been shown to be inaccurate for modeling breaking waves (case D). These tables for the case D waves should be revised in order to more accurately model breaking waves. These tables are most efficient for rapidly synthesizing nonlinear time series for time domain analyses.

Definitive guidelines should be provided which establish the use and applicability of the stream function tables for nonlinear wave designations. Task 4 should be conducted concurrently with Tasks 1 to 3 and prior to Tasks 5 to 9.

Task 5: Selection of Coefficients. Morison equation force coefficients for drag, inertia, and lift forces for relative motion structures must be computed from relative motion experiments and not from stiff, static models. Definitive guidelines are required to select the appropriate force coefficients for relative motion members for both time and frequency domain analyses. The frequency dependent coefficients may be suspect at high frequencies where the member may behave more like a large body

member in the diffraction wave force regime. Guidelines are also required for force loadings which treat the drag and inertia coefficients as constants over depth and time and are chosen to represent the entire force over depth and time. In addition, several linearization methods for the velocity and for the drag force have been given and the most appropriate coefficient selection with regard to the linearization process must be identified.

Definitive guidelines will be provided which document the SOA for the above-described coefficient selection technology. The significant experimental research will be documented in tabular summary format. The narrative will be cross-referenced to the tabular summary and will identify the relevance of coefficient selection to dynamic design problems in addition to a description of potential error magnitudes. Task 5 should be conducted subsequent to Tasks 1 to 4 and concurrently with Tasks 6 and 7.

Task 6: Wave-Current Loading. Wave-current interaction models for linearized random wave forces have been developed for the Morison equation. These models also treat the intermittent force loadings on members located above the wave troughs. Poisson distributions have been developed for these force loadings. Linearization methods for the wave plus current velocity have also been developed.

These developments will be identified in definitive guidelines. Significant results of previous research efforts will be provided in a tabular summary. Narrative explanations of the results will be cross-referenced to the tabular summary. Recommendations regarding the applicability of the wave-current interaction technologies to the dynamic design process will be provided in the design guidelines. Task 6 should be conducted subsequent to Tasks 1 to 4 and concurrently with Tasks 5 and 7.

Task 7: Wave Slamming. The problems associated with random wave slamming are similar to those for the deterministic waves. The primary difference is that the probability distribution must be a Poisson distribution since the members are located above the wave troughs. The design guidelines will incorporate this fact for the random dynamic analysis application. This task should be conducted subsequent to Tasks 1 to 4 and concurrently with Tasks 5 and 6.

Task 8: Frequency Domain Analysis. Frequency domain analyses must emphasize the linearization methods available. Iterative methods have been developed to minimize the linearization errors. The assumption of Rayleigh damping permits normal mode analyses. Guidelines on the Caughey minimization of the quadratic drag force and the Rayleigh damping are required. The quadratic drag force minimization requires knowing the root-mean-square relative velocity which requires an iterative procedure.

Frequency domain coefficients must also be selected with care, and guidelines are requried. Spectral moments and their application to modal damping are also important dynamic procedures which require attention in the guidelines.

These guidelines will document the current SOA for frequency domain analysis. Pertinent previous research results will be identified in a tabular summary format. The expert will cross-reference the narrative

report to the tabular summary of previous research. Design relevance, applicability, and error magnitudes of the frequency domain analysis relative to the time domain analysis will be identified. Computational expediency of the frequency domain analysis will also be addressed in the design guidelines. Task 8 should be conducted subsequent to Tasks 1 to 7 and concurrently with Task 9.

Task 9: Time Domain Analyses. Time domain analyses enjoy applications where the nonlinearities may be retained. Nonlinear stiffness and damping models deserve attention. Finite Element Method (FEM) solutions remove numerical instabilities found in Finite Difference Method (FDM) models and eliminate structural discretization constraints. Implicit time integration is preferred, and guidelines are required for selecting the most appropriate method for the nonlinear iterative algorithms. Efficient sparse matrix solvers as well as attention to symmetric stiffness matrices in nonlinear problems are required. Simulation methods for wave force loadings are critical and must be carefully reviewed.

A definitive design guideline is required to document the above described technology for Navy design applications. This design guideline will contain a tabular summary of previous research and results. The applicability of dynamic time domain Morison equation analysis will be stressed in the guidelines. Task 9 should be conducted subsequent to Tasks 1 to 7 and concurrently with Task 8.

Table J-1. Time Schedule: Morison Equation Random Dynamic Analysis Topics

Task	FY85				Remarks
	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	
1. Probability and Statistics					
2. Directional Wave Spectra					
3. Extreme Value Statistics					
4. Revise Stream Function Tables (Case D)					
5. Coefficient Selection					Accomplish with deterministic static work
6. Wave-Current Loading					Accomplish with deterministic static work
7. Wave Slamming					Accomplish with deterministic static work
8. Frequency Domain Analysis (linearized)					
9. Time Domain Analysis (nonlinear)					
10. Edit and Review Process					

Appendix K

WBS 3.4 DIFFRACTION THEORY ANALYSIS

Problem: As indicated in Figure K-1 and Figure B-2 of Appendix B, viscous effects become less significant as the diameter of the structural member increases. As a rule of thumb, the Froude-Krylov hypothesis is invalidated (and it is generally considered appropriate to ignore viscous effects and the attendant flow separation problems) when the ratio of the body diameter to wavelength (D/L) is greater than 0.2. Under these circumstances a solution via potential theory for irrotational, incompressible flow is indicated. Since the structure is large compared to the wavelength, the Froude-Krylov hypothesis is no longer valid; i.e., the structure's presence modifies the flow field significantly by scattering, or diffracting, the incident wave. Hence, these solutions are termed diffraction analysis. Figure 12 identifies one semi-empirical and five analytical types of diffraction analyses employed to date.

Existing NAVFAC guidelines need to be updated to specifically address these types of diffraction analyses and their range of application as well as their computational expediency. In order to provide a set of needed definitive guidelines for the hydrodynamic wave force analysis in the diffraction regime, it is necessary to review the level 3 SOA technologies identified in Figure 11. Table K-1 presents the time schedules.

Approach: Each of the diffraction theory analysis tasks identified in Figure 11 require definitive guidelines in order to establish the current state-of-the-art technology levels. This analysis technique has been important in the analysis of the large gravity base oil production structures in the North Sea and is employed in the analysis of semi-submersibles as well as proposed tension leg platform structures. Excellent research exists in the public domain regarding its use and application. This research needs to be summarized and incorporated where appropriate into a series of NAVFAC design guidelines for future inclusion in Navy design manuals. Tabular and graphical summaries must be compiled for each task by an expert intimately familiar with that particular field. These summaries will indicate the design relevance of each particular topic and indicate potential error magnitudes in the design analysis technique.

Task 1: Frequency Domain Linear Analysis: The more common forms of diffraction theory solutions indicated in Figure 13 are obtained in the frequency domain. These solutions are obtained via the small amplitude assumption and the consequential linearization of the kinematic and dynamic free surface boundary conditions. Several solution techniques such as the Ursell source distribution integral, the eigenfunction expansion of the Green's function, the Schwenger variational principal, the classic MacCamy-Fuchs (Ref 23) solution, etc., have been identified.

Guidelines are required to summarize their use, range of applicability, and computational efficiency.

Special attention will be given to the various forms of the Green's function diffraction theory solutions. Differences between the boundary integral and finite element techniques will be identified. Accuracy and computational expediencey comparisons for the approximate and explicit forms of the Green's function will be addressed. Simplified solutions for bodies of specific geometry such as vertical circular cylinders, axisymmetric bodies, etc., will be described. Solution techniques for fixed, moored, and freely floating diffraction bodies will be described.

These guidelines will be prepared by an expert in the field in a tabular summary format. The narrative will be cross-referenced to the tabular summary with design relevance and applicability specifically identified. Task 1 may be performed concurrently with Tasks 2, 3, and 4.

Task 2: Time Domain Nonlinear Analysis. The present SOA for diffraction analysis solutions is being extended to include the effects of nonlinear waves. These solutions are required to satisfy the nonlinear free surface kinematic and dynamic boundary conditions to a higher order error approximation. Guidelines should be established which document this research and make it available as appropriate for Navy use. The time domain solutions for axisymmetric bodies, bodies of separable geometries, bodies with two-dimensional geometries, and bodies of arbitrary geometry should be addressed independently. Perturbation techniques such as the Stokes expansion procedures and the Friedrich's shallow wave expansion procedures discussed by Isaacson (Ref 24) should be described. Error estimates for the linear versus nonlinear diffraction analysis and their range of applicability will be established.

These guidelines should be prepared in a tabular summary format in which all pertinent previous research is documented and referenced. Narrative explanations of the research will be referenced to the tabular summary. Applicable software available in the public domain or for sale within the industry, as well as error magnitudes and design relevance, will be identified. Task 2 may be performed concurrently with Tasks 1, 3, and 4.

Task 3: Mooring Effects. The effects of moorings on the diffraction analysis of large bodies need to be summarized in a set of design guidelines. This work must incorporate the research conducted by NCEL in the Mooring Dynamics Investigation program. These guidelines should specifically address the SOA capabilities in assessing nonlinear material and geometric effects in mooring analysis. The guidelines must also summarize the structure-mooring interaction regarding simultaneous and iterative solution techniques.

Types of mooring tethers proposed for offshore structures will also be examined. A comparison between solid cylindrical tethers versus stranded cable moorings will be provided as a function of displacement, buoyancy, mooring geometry, and fluid loading.

These guidelines will be provided by an expert in the field and will summarize the available SOA technology for the mooring topic for ocean structures. These guidelines will summarize this research in

tabular format. Design relevance and error magnitudes will be provided. Task 3 may be performed concurrently with Tasks 1, 2, and 4.

Task 4: Drift Force Effects. Second-order steady drift forces on ocean structures arise by virtue of nonzero temporally averaged second-order wave forces. Although a second-order force, drift force magnitudes for tethered platforms are of important design significance. Issacson (Ref 24) has noted that these forces are particularly important for random wave loading since the drift force varies slowly with time thereby exciting a low frequency resonance in the mooring system. Guidelines are needed to describe these effects and their design relevance. These guidelines must incorporate the research conducted by NCEL in the Mooring Dynamics Investigation program. The guidelines should, again, be presented in tabular summary format. This task may be conducted concurrently with Tasks 1 to 3.

Task 5: Random Wave Loading. Definitive guidelines are required to summarize the effects of random seas and random wave loading on diffraction-type structural members. These effects should be specifically referenced to both the linearized frequency domain analysis and the achievement of a nonlinear random time domain diffraction analysis technique. Random wave effects must also be summarized for the topics of mooring dynamics and drift forces. Spectral representations of the random wave process and their relevance to the design processes described earlier will be identified. These guidelines will summarize the SOA for research efforts regarding this technology and will stress the applicability to Navy offshore structure design requirements. The format will be a tabular summary with a cross-referenced narrative. This task should be conducted subsequent to Tasks 1 to 4 and concurrently with Tasks 6 to 8.

Task 6: Free Surface Effects. The linearization process employed in small amplitude theory approximates the free surface at the still-water level. This leads to errors in the computed pressure distribution above the free surface. Ideally, the predicted pressure at the free surface must be zero (atmospheric gage pressure). Corrections for the linearized diffraction theory should be applicable for two dimensionless velocity heads below the instantaneous free surface.

The effects of surface run-up and run-down fore and aft of the member, respectively, will be examined. The definitive guidelines addressing these topics will be provided in a tabular form. Pertinent previous research will be summarized in detail by an expert. Recommendations regarding the design relevance of this topic and potential error magnitudes will be provided. This task should be performed subsequent to Tasks 1 to 4 and concurrently with Tasks 5, 7, and 8.

Task 7: Damping Effects. Diffraction theory ignores the viscous effects associated with flow separation and vortex shedding. Generally speaking, these viscous effects are small. Locally, however, viscous effects may be an important consideration such as at joints, corners, and appendages. Radiated wave damping effects and the damping due to free surface interactions should also be addressed. These guidelines will be provided by an expert in the field and will review the SOA.

Pertinent results will be summarized in a tabular fashion. This task should be accomplished subsequent to Tasks 1 to 4 and may be accomplished concurrently with Tasks 5, 6, and 8.

Task 8: Wave Slamming Effects. Design guidelines for wave slamming on large diffraction-type members is described appropriately in Task 4 of Appendix I and Task 7 of Appendix J.

Table K-1. Time Schedule: Diffraction Theory for Large Structural Members

Task	FY86				Remarks
	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	
1. Frequency Domain Linear Analysis					
2. Time Domain Nonlinear Analysis					
3. Mooring Effects					
4. Drift Force Effects					Combine with Task 3
5. Random Wave Loading Effects					Combine with Tasks 1 and 2
6. Free Surface Effects					
7. Damping Effects					
8. Wave Slamming Loading					
9. Edit and Review Process					

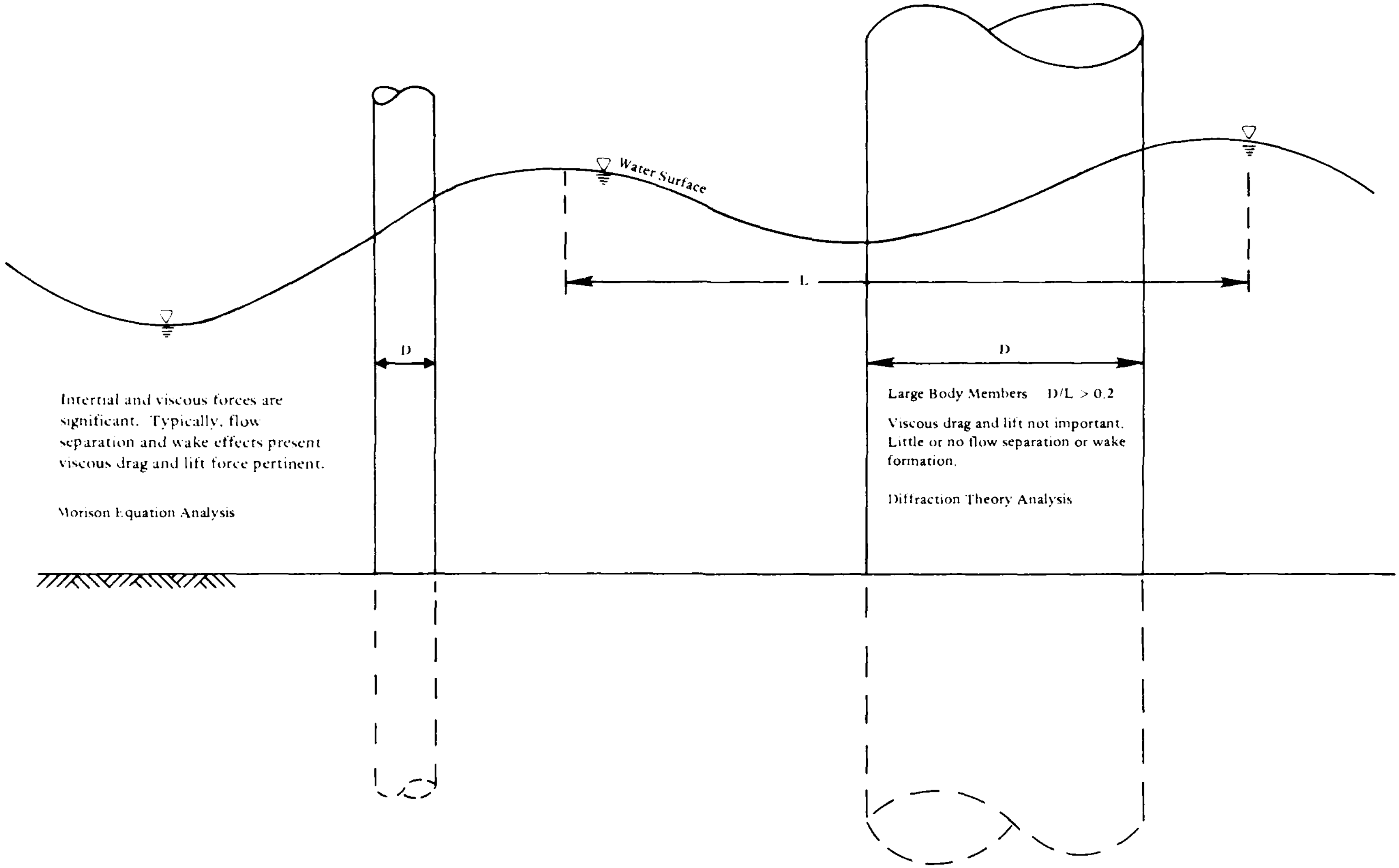

Figure K-1. Comparison of structural dimensions to wave length dimensions.

Appendix L

WBS 3.5 COMBINED MORISON EQUATION AND DIFFRACTION ANALYSIS FOR COMPOSITE STRUCTURES

Problem: A number of currently deployed and several proposed types of ocean structures employ both large and small (diameter relative to the wavelength) structural members. Consequently, a hydrodynamic loading analysis by pure Morison equation techniques or by diffraction theory is inappropriate. Either method alone introduces errors related to viscous damping and flow separation effects. That is, the Morison equation analysis inappropriately includes viscous forces for the large structural members while overpredicting the inertial forces, whereas the diffraction theory analysis ignores the viscous drag forces on the smaller members. Methods of analysis for rigid, large, and small member composite structures, such as North Sea gravity platforms, have been devised which appropriately model the viscous effects. These methods require that a solution for the incident and scattered wave velocity potentials be obtained via diffraction theory for the large body alone. This is appropriate if the Froude-Krylov hypothesis is invoked for the small members; i.e., they have no effect on the incident flow field. Once the incident and scattered velocity potentials are obtained from the diffraction analysis the appropriate local velocities about the small members can be modeled and viscous drag forces can be calculated.

This problem becomes more complicated if the composite structure is not held fixed as in the case of tension leg platform structures and semi-submersibles. The solution technique is, however, the same with the diffraction problem being solved first. The Morison equation analysis is then performed using relative velocities from the diffraction velocity potentials and the predicted structural motions without viscous damping. This approach can be applied iteratively to fine-tune the solution. Finite element solutions are also being developed which simultaneously solve the composite fluid structure interaction problem.

Existing NAVFAC design guidelines do not address this composite structures problem and should be updated to include these solutions. The six level 3 topics shown in Figure 11 must be specifically addressed in order to provide this set of comprehensive and definitive design guidelines. Table L-1 presents the time schedule.

Approach: Each of the six level 3 topics shown in Figure 11 needs to be described in a comprehensive, definitive design guideline. These guidelines should be provided by a noted expert in that particular topic. The guidelines should each summarize the SOA and SOP technology levels and all previous pertinent research. The design relevance and the potential error magnitudes associated with each individual task will be specifically identified.

Task 1: Modeling the Modification of the Kinematics and Pressure Fields. As described in the presentation of the Problem, in the analysis of composite structures it is necessary to be able to perform both Morison equation and diffraction theory hydrodynamic force modeling. The Froude-Krylov hypothesis that the presence of the structure does not modify the incident wave field is no longer valid for the large members; hence, a diffraction analysis is required to obtain the incident, scattered, and radiated wave velocity potentials. The pressure field is obtained from the velocity potential solution via the Bernoulli equation and may be integrated over the large body members to obtain the large body hydrodynamic loading. The achieved velocity field solution is used to predict required local kinematics for the Morison equation small body hydrodynamic load analysis. However, for compliant structures the small and large body effects are not mutually exclusive. These effects and the appropriate modifications to the theoretical kinematics and pressure fields must be described in a definitive design guideline. SOA software for solving these problems will be described in detail. Specific emphasis will be placed on the solution of the simultaneous fluid-structure interaction problem without iterative methods. Computational efficiency and applicability of numerical models will be identified in the guidelines. The relevance of the viscous effects and error magnitudes if they are ignored will be included. The significance of nonlinear effects in the linear diffraction theory portion of the composite analysis will also be identified. Time domain nonlinear solutions will be described with estimates of computational accuracy, time, and effort required for the analysis will be provided. Random wave loading effects will also be determined.

This guideline will be prepared by an expert in the field with a tabular review of previous research and results and supplemental cross-referenced narrative. This must be the first task accomplished.

Task 2: Selection of Coefficients. This task is similar to those for the deterministic static and random dynamic Morison equation analysis tasks as described in Task 1 of Appendix I and Task 5 of Appendix J. The essential difference to be described in these guidelines is the effect of simultaneously translating and rotating small body members on floating structures. The relevance of these effects and the potential errors will be stressed for the design mode. This task should be performed subsequent to Task 1 and concurrently with Tasks 3 to 5.

Task 3: Interference Effects. Interference effects due to both the presence of the large members and their attendant diffraction of the incident wave and the small members' vortex shedding and wake formation must be established in definitive design guidelines. The effects of interacting large body diffraction members has been addressed by Issacson in one portion of Reference 24, while the interference effects of small bodies has been described by Sarpkaya in another section of Reference 24. However, the simultaneous effects of both large and small members should be reviewed and summarized in the design guidelines. The appropriateness of performing a diffraction theory analysis without reference to the interaction of the small body members will be identified. The guidelines will specifically address the pertinence and application of these effects in the design process. This task should be performed subsequent to Task 1 and concurrently with Tasks 2, 4, and 5.

Task 4: Mooring Effects. The effects of moorings on composite structures should essentially be the same as the effects described for pure diffraction structures in Task 3 of Appendix K.

Task 5: Wave Slamming. Design guidelines for wave slamming on large and small body members is adequately described in Task 4 of Appendix I and Task 7 of Appendix J.

Task 6: Damping Effects. For composite large and small body structures viscous damping due to vortex shedding and wake effects cannot be ignored. In addition, radiated wave-making damping is also an important research topic for floating bodies such as tension leg platforms. The interactive damping, when both forms are present, needs to be addressed in a definitive design guideline. Design relevance and potential error magnitudes need to be addressed. Interference effects and damping effects must be cross-correlated in the guidelines. Pertinent previous research will be summarized in detail by an expert in the field. This task should be accomplished subsequent to Tasks 1 to 5.

Table L-1. Time Schedule: Combined Morison Equation and Diffraction Analysis for Composite Structures

Task	FY86			FY87	Remarks
	2nd Qtr	3rd Qtr	4th Qtr	1st Qtr	
1. Modeling the Kinematics and Pressure Field Modification					
2. Coefficient Selection					
3. Interference Effects					
4. Mooring Effects					From Diffraction Task 3
5. Wave Slamming Effects					From Morison Equation Static Task 4 and Random Task 7
6. Damping Effects					
7. Edit and Review Process					

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COMNAVSURFLANT Norfolk, VA
COMSUBDEVGRUONE Operations Offr, San Diego, CA
COMUSNAVCENT N42, Pearl Harbor, HI
NAVSURFPAC Code N-4, Coronado
COMOPTEVFOR CMDR, Norfolk, VA; Code 705, San Diego, CA
DEFFUELSUPPCEN DFSC-OWE (Term Engrng) Alexandria, VA
DLSIE Army Logistics Mgt Center, Fort Lee, VA
DNA STTL, Washington DC
DOE Div Ocean Energy Sys Cons/Solar Energy Wash DC
DTIC Defense Technical Info Ctr/Alexandria, VA
DTNSRDC Anna Lab (Code 119) Annapolis MD; Anna Lab (Code 1568) Annapolis MD
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